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Optimal speed limit for shared-use roadways

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ABSTRACT

OPTIMAL SPEED LIMIT FOR SHARED-USE ROADWAYS

by
Yongqiang Yang

Motor vehicle crashes are a serious social problem in the United States. Each year a large number of motor vehicle crashes occur and many people are killed or injured, resulting in substantial economic costs. To minimize economic costs, it is necessary to determine optimal speed limits on roadways because of the strong relationship among posted speed limit, crash frequency, and crash injury severity.

A comprehensive literature review about the relationship among posted speed limit, crash frequency, and crash injury severity level was conducted. Crash frequency prediction models and crash injury severity models are developed to obtain crash frequency and injury severity of victims in motor vehicle crashes at different posted speed limits. Model tests were also performed to verify the model fitness of data. Crash costs were then calculated based on crash frequency, injury severity level, and unit cost of each severity level. In addition, CORSIM simulation was used under various posted speed limits to obtain parameters related to operational cost. Total cost curves were then built to show the relationship between posted speed limit and total economic cost.

Using the developed crash frequency models, injury severity models and CORSIM simulation results, case studies were conducted to determine optimal speed limits on selected roadways. The results determined optimal speed limits on specific roadways on the basis of total cost.

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by

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To my beloved family

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CHAPTER 1

INTRODUCTION

Motor vehicle crashes are a serious social problem in the United States. Each year a large number of motor vehicle crashes occur and many people are killed or injured. Moreover, pedestrians and bicyclists are involved in motor vehicle crashes at high rates. In 2003, there were 33,574 vehicle occupant, 5,649 pedestrian and 816 bicyclist fatalities in motor vehicle crashes in the United States. Additionally, 2,978,000 vehicle occupants, 94,000 pedestrians and 68,000 bicyclists were injured in crashes (NHTSA, 2003). In 2003, 589 vehicle occupants, 147 pedestrians and 11 bicyclists were killed in traffic crashes in the State of New Jersey (NHTSA, 2003), indicating the serious problem caused by traffic crashes in New Jersey.

In 1994, *the National Bicycling and Walking Study* was released by the Department of Transportation. The study included two overall goals, the first one was to increase the percentage of total trips generated by bicycling and walking in the United States from 7.9 percent to 15.8 percent of all travel trips; and the second goal was to decrease by 10 percent the number of bicyclists and pedestrians killed or injured in motor vehicles crashes. To achieve these objectives, it is important to provide pedestrians and bicyclists with enhanced travel safety, while at the same time encourage more people to travel by walking or bicycling.

One of the important factors impacting the safety of road users is vehicle travel speed since a lot of previous studies as shown in Chapter 2 proved the relationship among speed, crash injury severity, and crash frequency. Also, previous studies showed the impact of changes in posted speed limit on vehicle travel speed. Therefore, determining appropriate speed limits for various types of roadways is a possible approach to improve safety for road users including pedestrians and bicyclists who share the roadway with motor vehicles. As motor vehicle crashes may result in property damage, injuries or even fatalities, great losses including direct costs such as property damage, emergency medical service (EMS), medical treatment, and indirect costs such as insurance premiums are inevitable. The ability to set appropriate speed limits to minimize costs induced by traffic crashes for shared roadway conditions has become increasingly important.

1.1 Problem Statement

When determining speed limit for shared traffic roadways, it is necessary to consider not only travel safety for vehicle occupants, pedestrians, and bicyclists, but also travel time, fuel consumption, and air pollution. However, posted speed limits are set up across the world based on engineering and traffic investigations without accounting for the total cost induced by traffic crashes. Therefore, the use of optimal speed limits based on total costs is one approach that can be used for setting speed limits that account for shared uses of the roadway. The optimal speed limit defined by previous researchers as the minimum point on the total cost curve, where total cost consists of crash cost, travel time cost, and emissions cost. Little research, however, has focused on identifying the optimal speed limit in terms of total cost analysis for specific types of roadways such as shared-use roadways. Moreover, no study was found that estimated traffic crash cost by using both predicted crash frequency and injury severity level sustained by victims in traffic crashes.

1.2 Research Objectives

This research is focused on developing a total cost function for determining the optimal speed limit, which is the minimum point on the total cost curve. The main objectives of this study are as follows:

1. Develop crash prediction models to forecast crash frequency with respect to specific roadway types, both for urban and rural areas.

2. Develop ordered probit models to identify the relationship between injury severities sustained by vehicle occupants, pedestrians or bicyclists and a set of independent variables including the posted speed limits on the roadways, and to predict injury severity sustained by the victims.

3. Develop an Operation Module, which can be used to identify the operational performance level for various speed limits. CORSIM simulation was used to obtain vehicle travel time, and vehicle emissions in different speed limits.

4. Conduct total cost analysis by calculating total cost, which consists of crash cost, travel time cost, fuel cost, and vehicle emissions cost. Total cost curve is then built, and the optimal speed limit is determined according to the curve since it corresponds to the lowest cost.

5. Apply the above models to specific shared-use roadways in New Jersey to determine optimal speed limits on these roadways.

1.3 Dissertation Organization

This dissertation consists of six chapters. Chapter 1 presented an introduction to the dissertation, stating the specific problem to be addressed in the research and the research objectives. Chapter 2 provides a literature review on the relationships among speed limit, vehicle speed and injury severity, between speed limit and operational cost, and the criteria used for setting speed limits in different countries as well as in the United States. Chapter 3 presents a methodology of the models to be used. Chapter 4 gives model results obtained from the developed models. Chapter 5 shows case studies by applying the methodology of this research to several specific roadways. Chapter 6 contains the conclusions of this research.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a literature review on the following studies: (1) speed limit, vehicle speed and safety to determine the relationship among speed limit, vehicle speed and crash incidence as well as the relationship among speed limit, vehicle speed and injury severity caused by crashes, including both vehicle-vehicle crashes and vehicle-pedestrian/bicycle crashes; (2) criteria for setting speed limits in different States in the U.S. and in other countries; (3) review of determination of optimal speed limit; (4) the correlation of speed limit and operational cost of motor vehicle; (5) existing models which had been developed to obtain the relationships among vehicle speed, crash frequency, and crash injury severity.

2.1 Speed Limit and Safety

It is a common understanding that speed plays a very important role in traffic safety. Speeding contributed to about 39 percent of all fatal motor vehicle crashes in the U.S. in 2001 (NHTSA, 2001). Moreover, it has been well known that speeding imposes much more risk on pedestrians and bicyclists compared to vehicle occupants involved in vehicle crashes. Pedestrians and bicyclists do not have protection available through vehicle safety equipment such as airbags and seat belts, and for this reason are more vulnerable in a motor vehicle crash. It is also well known that speed is one of the most important factors impacting injury severity once a crash occurred. This can be proved by the law of physics, namely, Kinetic Energy= $0.5*Mass*Speed^2$. Section 2.1 presents traffic safety statistics, and the relationship among speed limit, vehicle travel speed, crash frequency, and crash injury severity.

2.1.1 Traffic Safety Statistics

Nationally, there were approximately 40,000 fatalities and 300,000 injuries in motor vehicle crashes each year in the last 10 years (NHTSA, 2003). Table 2.1 shows the number of vehicle occupants, pedestrian and bicyclist fatalities and injuries in the U.S. from year 1994 to 2003. It can be seen from the table that about 35,000 vehicle occupants, 5000 pedestrians, and 750 bicyclists were killed in motor vehicle crashes each year, and that there is a large number of injuries as a result of these crashes, indicating the serious problem on traffic safety.

Table 2.1 Numbers of Fatalities and Injuries for Road Users

Year	Fatal			Injury		
	Vehicle Occupant	Pedestrian	Bicyclist	Vehicle Occupant	Pedestrian	Bicyclist
1994	34,318	5,489	802	3,102,000	92,000	62,000
1995	35,291	5,584	833	3,303,000	86,000	67,000
1996	35,695	5,449	765	3,332,000	82,000	58,000
1997	35,725	5,321	814	3,201,000	77,000	58,000
1998	35,382	5,228	760	3,061,000	69,000	53,000
1999	35,875	4,939	754	3,097,000	85,000	51,000
2000	36,348	4,763	693	3,055,000	78,000	51,000
2001	36,440	4,901	732	2,901,000	78,000	45,000
2002	37,375	4,851	665	2,800,000	71,000	48,000
2003	37,132	4,749	622	2,764,000	70,000	46,000

Source: Traffic Safety Facts 2003-Overview, NHTSA 2003

2.1.2 Speed Limit and Travel Speed

A wealth of studies has been conducted to show the relationship between posted speed limit and vehicle travel speed. Much research were focused on the impact of the 55-mph national maximum speed limit (NMSL) in 1974, which was caused by the fuel crisis in that year, and the impact of the repeal of NMSL in 1985 on vehicle travel speeds, accident frequency, and injury severity. Burritt et al. (1976) investigated the relationship between traffic accident frequencies and traffic fatalities in Arizona in 1974 and the 55-mph NMSL. Highways with speed limit exceeding 55 mph before 1974 were selected in the study. Accident data were obtained from the Arizona Department of Transportation highway accident records for 1973 and 1974. The authors compared mean vehicle speed and traffic fatalities on selected highways in the two-year period. The result showed that travel speeds fell from a range of 5 mph to 8 mph on different highways with the enactment of the 1974 NMSL, and moreover, the authors attributed the reduction in traffic fatalities, injury, property damage only crash (PDO), and total accident rates to both the reduced vehicle travel speed and the speed differential within the traffic stream. A study conducted by Dart (1977) also showed that the 55-mph speed limit reduced both the average vehicle speed and the speed differential on all classifications of highways.

As a result of mitigated fuel crisis and lower fuel prices in the 1980s, the NMSL was repealed and speed limits were raised from 55 mph to 65 mph on rural interstate highways in 1985. Studies were then conducted to investigate the impact of the increased speed limit on travel speed and crash fatalities.

Upchurch (1989) presented the experience with the 65-mph speed limit in Arizona after the speed limit was increased in rural interstate highways. Before and after vehicle speeds were obtained to evaluate the effect of the 65-mph speed limit. The results showed that vehicle travel speed increased by about 3 mph following the 10 mph increase in posted speed limit. Later, a study conducted by Brown et al. (1990) used Alabama accident records to evaluate the safety impact of the 65 mph speed limit. The two accident data sets, one year before and one year after the speed limit change, were obtained to compare accident frequency and injury severity. The authors pointed out that average speed increased by about 2 mph with the increased speed limit. The strong relationship between speed limit and vehicle travel speed were also proved by Freedman et al. (1990), and Jernigan et al. (1991).

Jernigan and Lynn (1991) also showed in Table 2.2 the speed data during a five-year period in selected states, including those increasing speed limit to the 65 mph and those remaining at the 55-mph speed limit. It can be seen from the table that the average speed and 85th percentile speed increased much more in states with speed limits that were originally higher.

Table 2.2 Average and 85th Percentile Speeds on Rural Interstate Highways

Year	Speed, mph					
	States with 55-mph Speed Limit (n=6)		States with 65-mph Speed Limit (n=19)		Virginia	
	Average	**85th Percentile**	**Average**	**85th Percentile**	**Average**	**85th Percentile**
1986	58.9	65.9	60.7	66.7	56.3	62
1987	59.7	66.3	61.7	68.7	59.9	65
1988	60.6	67.8	63.1	69.2	60.1	66
1989	61.3	68.2	64.4	70.9	63.5	70
Change 86-89	+2.4	+2.3	+3.7	+4.2	+7.2	+8

Source: Jernigan and Lynn, 1991

Since the studies above were focused on limited access rural interstate highways, it is necessary to review the effect of speed limit change on non-limited access roadways. Parker (1997) conducted a study to evaluate the effect of raising or lowering posted speed limits on driver behavior and accidents for non-limited access rural and urban roadways. Speed and accident data were obtained from 100 sites in 22 states before and after posted speed limits were changed. Also, speed and accident data during the same time period at sites where speed limits were not changed were collected to make comparison. The author concluded that lowering and raising posted speed limits had minor impact on vehicle travel speed. Table 2.3 showed the change of mean speed and 85th percentile speed with the change of speed limits.

Table 2.3 Before and After Mean and 85^{th} Percentile Speed on Non-Limited Access Roadways

	Experimental Sites				Comparison Sites			
Delta SL	Average Mean Speed (mph)		Average 85^{th} Speed (mph)		Average Mean Speed (mph)		Average 85^{th} Speed (mph)	
	Before	After	Before	After	Before	After	Before	After
-15	42.1	42.2	49.1	49	47.7	47.7	55.6	55.4
-10	42.7	42.7	50	49.9	47.8	48.1	55.3	55.5
-5	43.7	43.7	50.7	50.4	46.2	46.4	53.1	52.9
+5	41.9	42.2	48.5	48.4	40.5	40.4	47	46.8
+10	36.7	37.5	43.3	43.8	32.9	32.9	39.5	38.8

Source: Parker (1997)

In the research above, the author also reviewed previous studies on the effect of speed limit change on non-limited access roadways, which are shown in Table 2.4. It can be seen from the table the change in posted speed limits had impact on vehicle travel speeds, but it did not create equivalent changes.

Table 2.4 Before and After Mean and 85th Percentile Speed on Non-Limited Access Roadways

Location	Author	Year	Section No	Posted Speed Limit		Average 85th Percentile Speed	
				Before	After	Before	After
St. Paul,	Avery	1960	7	30	35	35.5	35.8
			4	30	40	39.4	40.8
West Lafayette	Elmberg	1960	1	35	30	38.4	38.5
St. Joseph, IL	Ogawa	1962	1	30	35	30.6*	31.3*
Orden, IL			1	40	35	32.2*	33.3*
Fithian, IL			1	35	40	34.9*	35.3*
Columbia, SC	Roberts	1967	1	35	40	42.5	41
3 urban Areas, TX	Dudek	1986	6	55	45	55.9	54
Washington		1981 -1982	3	25	30	34.7	34.3
			1	50	55	57	59
			1	50	35	43	42
			3	40	35	45	43.7
Michigan		1982	4	25	35	37.6	36
			4	55	50	56.8	54.8
			4	55	50	57.8	56
			5	45	35	49.2	47

Source: Parker (1997), * denotes mean speed instead of 85th percentile speed

2.1.3 Speed Limit and Crash Frequency

Results of research on the effect of speed limit on crash frequency varied in previous studies. Scharping (1994) reported a 20 percent decline of traffic crashes on urban roads in Hamburg City in Germany after the posted speed limit was reduced from 37 mph to 31 mph. Peltola (1991) found that crashes decreased by 14 percent with the posted speed limit being decreased from 62 mph to 50 mph. However, Parker (1997) obtained opposite result in his research. The author found that crashes increased by 5.4 percent at the 58 experimental sites on non-limited access rural and urban roadways where speed limits were decreased, while crashes decreased by 6.7 percent at the 41 experimental sites where speed limits were increased.

As mentioned above, change in posted speed limits has effect on vehicle travel speed for shared roadways, although the changes are not equivalent. Therefore, it is necessary to study the relationship between vehicle speed and crash frequency. Researchers also made conflicting conclusions about the impact of speed on crash frequency. In TRB Special Report 254 (TRB, 1998), the authors pointed out that a higher speed is more likely to cause a crash, although motor vehicle crashes are complicated issues and may be impacted by other factors. In this report, the authors also stated that there was a strong positive relationship on urban streets between crash probabilities and speed of the crash-involvement vehicles. Research conducted by Bowie and Walz (1994) showed that in all road categories, urban streets made up the highest percentage of fatal crashes caused by speeding (TRB, 1998).

Kloeden et al. (1997) used a case control study model to compare the crash-involvement vehicle speeds with speeds of vehicles not involved in crashes but traveling in the same direction, under the same weather and light conditions, at the same location, time of day, day of week, and time of year. The findings showed a small reduction in traveling speed could greatly decrease crash and injury frequency in rural roads. For example, a 3 mph speed reduction of traveling vehicles would result in a 31 percent reduction in casualty crashes.

Later, Davis (1998) developed a deterministic model to predict probability of pedestrian-vehicle collision and related collision speed. Parametric and nonparametric estimation methods were used separately to determine collision likelihood. Davis used a parametric estimation if vehicle speeds obeyed appropriate distribution forms, and the relationships among traffic flow, vehicle speed and pedestrian safety were then determined. If vehicle speeds did not follow appropriate distribution forms, the nonparametric estimation was used to forecast collision probability at specific sites where traffic calming measures, such as measures used for decreasing traffic volume and lowering vehicle speeds, would most likely impact the probability of collision. The results showed that sites with the highest average travel speeds also had the highest likelihood of pedestrian-vehicle collision probability.

In addition, a wealth of studies has been conducted to study the relationship between vehicle speeds and crash probability. Some of these studies include work performed by Kim and Li (1996), Stutts et al. (1996), Russell (1990), Do (2002), and McMahon et al. (1999). Results from their research showed that increase in vehicle speed led to increasing crash probability.

As for the reason of the relationship between speed and crash probability, Zegeer et al. (2002) indicated that it is more difficult for drivers at higher speeds to see pedestrians, and it is even much more difficult to stop the vehicle to yield to pedestrians.

In addition, stopping distance will be longer for higher speed vehicles than that of lower speed vehicles. For vehicles traveling at 31 mph, stopping distance will be 200 ft whereas the number will decrease to about 100 ft for vehicles traveling at 19 mph speeds.

There were other studies, however, showing different results on the relationship between vehicle speed and vehicle crash likelihood. Solomon (1964) conducted a study on relating vehicle travel speed to vehicle crash involvement rate. Data in his study are obtained from crashes occurring on 35 selected rural highway sections with a total length of 600 miles in 11 States in the U.S. The data set included information from police reports involving 10,000 drivers who were involved in accidents, and information on speed measurements and survey data from 290,000 drivers who were not involved in accident. The speeds of accident-involved and non-involved drivers were then compared to show the relationship between speed and accident involvement rate. The result indicated a U-shape relationship between crash involvement rate and travel speed, which is shown in Figure 2.1. As can be seen from the diagram, crash involvement rate was greatest for vehicles traveling at 22 mph, and then the rate gradually decreased until it achieved its lowest rate at 65 mph traveling speed, and then the rate increased again with increasing travel speed. In the same study, Solomon also compared travel speeds of crash vehicles with average free flow speed of other vehicles on two and four lane, non-limited access rural highways. Based on this comparison, a U-shape curve was also built as shown in Figure 2.2, which showed a strong relationship between speed deviation and vehicle crash involvement rate. Later, the same conclusion of U-shape relationship was achieved by Cirillo (1968), who studied U.S. Interstate highways, and by Harkey et al. (1990), who based their research on rural and urban roads with posted speed limits from 25 to 55 mph in two U.S. states. The U-shape curve showed that a vehicle was more likely to be involved in a crash when the deviation between the vehicle's speed and the average speed of vehicles was larger, indicating that vehicles with too fast or too slow speed were more likely to be involved in an accident.

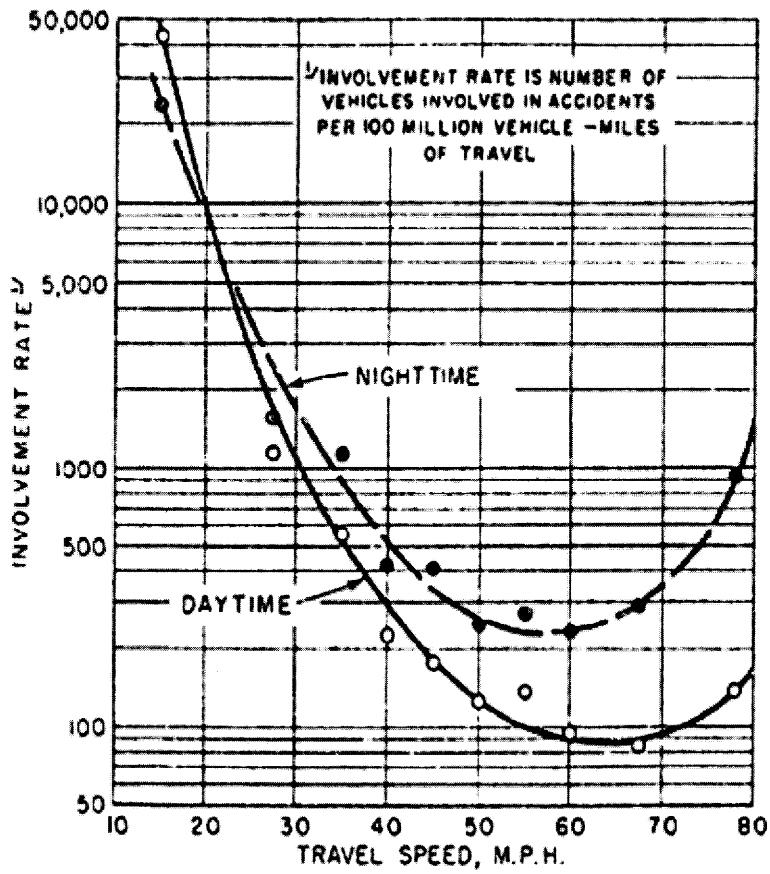

Figure 2.1 Relationship between travel speed and crash involvement rate.
(Source: Solomon, 1964, cited in Kloeden et al. 1997)

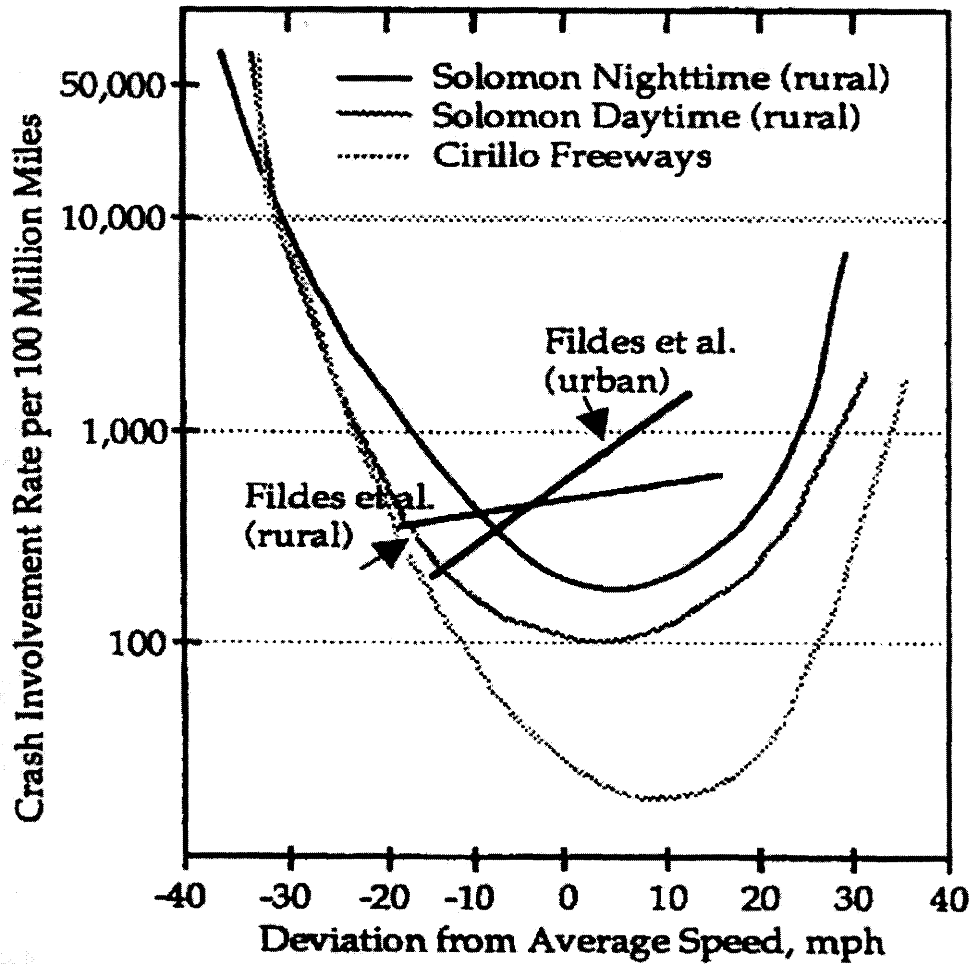

Figure 2.2 Relationships between vehicle crash involvement rates and deviation from average traffic speeds.
(Source: TRB1998)

Garber and Gadirau (1988) also found a negative relationship between average vehicle speed and crash freqency. Data applied to the research were obtained from 36 sections on seven types of Interstate highways in Virginia. The result indicated that crash frequency rose by about 7 percent at locations where speed limits were reduced, and fell by about 11 percent at locations where speed limits were raised when compared with locations where speed limits remained unchanged. The negative relationship between speed and crash frequency was attributed to the fact that drivers were more likely to drive with higher speed on roads with better geometric characteristics.

2.1.4 Speed Limit and Injury Severity

The results from a majority of studies were consistent that both speed limit and vehicle speed have a positive impact on injury severity. This means that injury severities are more likely to be serious with the increase in speed limit, and less serious with the reduction in speed limit. Jensen (1998) conducted a study to determine the effect of lowering speed limits in Denmark on injury severity of pedestrians and bicyclists. The result showed a 25 percent reduction in occurrence of pedestrian crashes for all injury severity levels. When the urban speed limit was reduced from 37.5 mph to 30 mph in 1985, average vehicle travel speeds decreased by 1.25-1.875 mph, and pedestrian fatalities, serious injuries and slight injuries dropped by 31%, 4%, 9%, respectively. Figure 2.4 shows pedestrian injury trends in Denmark from 1950 through 1997. In Denmark, national speed limits were reduced several times starting from 1974 to 1997. The figure indicates a declining trend of pedestrian injuries during that period. In addition, Figure 2.5 shows a strong relationship between posted speed limits and pedestrian injury severities. Based on the pedestrian injury data during the period of 1986-1985, no pedestrian was killed on the roadways with speed limits 15 or 20 km/h, whereas 35 percent of pedestrians were killed when struck by motor vehicles on roadways with speed limits 110 km/h.

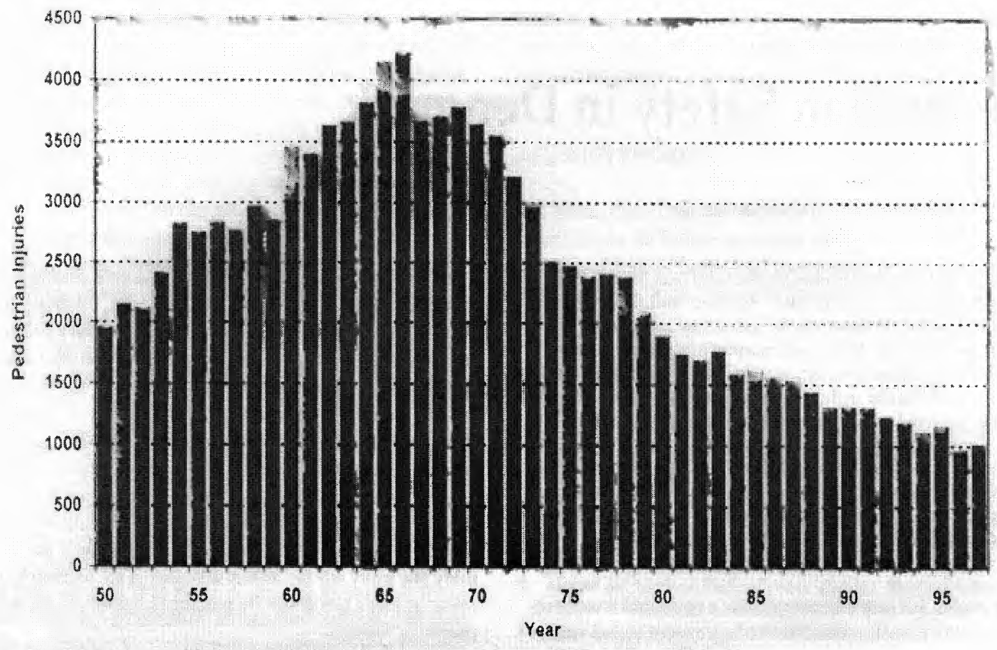

Figure 2.3 Pedestrian injuries in Denmark.
(Source: Jensen 1999)

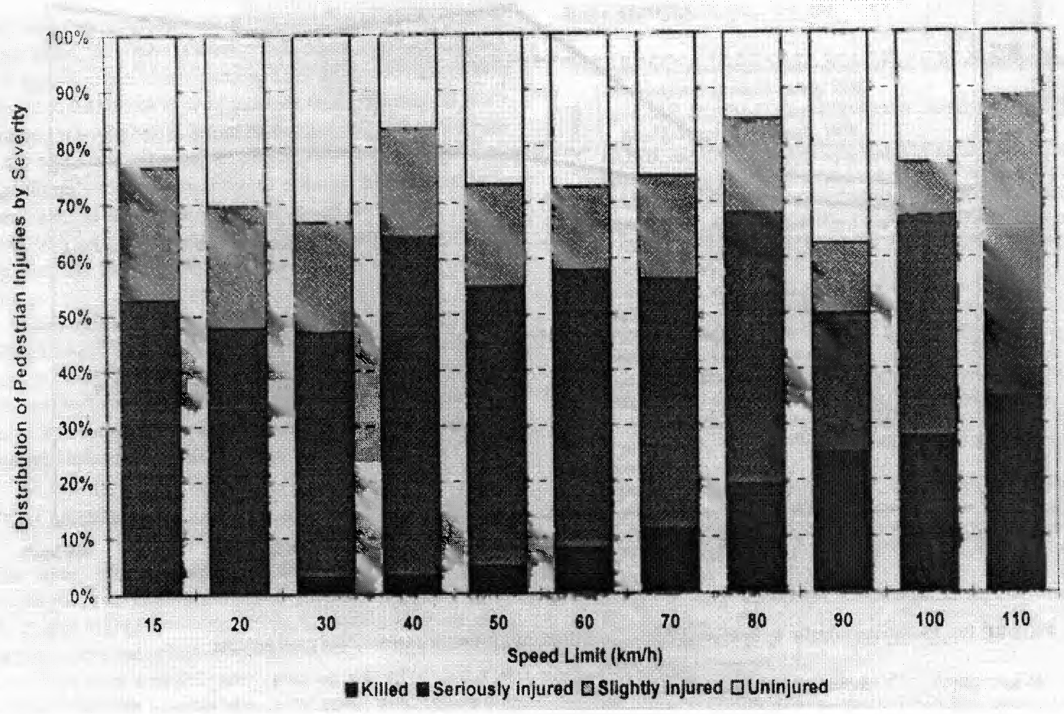

Figure 2.4 Pedestrian injuries by severity and speed limit.
(Source: Jensen 1999)

For crashes involved in vehicle and vehicle, Duncan (1998) pointed out a higher speed limit increases injury severity level sustained by vehicle occupants when the car was involved in truck-passenger car rear-end collisions. A study conducted by Stuster and Coffman (1998) summarized the effect of lowering or raising the speed limit on injury severity for vehicle occupants. This summary is presented in Table 2.5. The table shows that injury severity increase with the increase of speed limit, and decrease with the reduction of speed limit.

Table 2.5 Effect on Injury Severity of Lowering or Raising Speed Limit

Reference	Country	Speed Limit Change (mph)	Results
Speed Limit Decreases			
Nilsson (1990)	Sweden	68 to 56	Fatal crashes declined by 21%
Engel (1990)	Denmark	37 to 31	Fatal crashes declined by 24%
Sliogeris (1992)	Australia	68 to 62	Injury crashes declined by 19%
Finch et al. (1994)	Switzerland	81 to 75	Fatal crashes declined by 12%
Speed Limit Increases			
NHSTA (1989)	USA	55 to 65	Fatal crashes raised by 21%
McKnight et al. (1990)	USA	55 to 65	Fatal crashes raised by 22%
Garber and Graham (1990)	USA	55 to 65	Fatal crashes raised by 15%
Streff and Schultz (1991)	USA	55 to 65	Fatal and injury crashes raised
Sliogeris (1992)	Australia	62 to 68	Injury crashes raised by 25%
Iowa Safety Task Force (1996)	USA	55 to 65	Fatal crashes raised by 36%

Source: Stuster and Coffman (1998)

As for the effect of vehicle travel speed on injury severity for vehicle occupants, Solomon (1964) pointed out that injury severity was more serious with increasing travel speed on rural roads. Based on the analysis of 10,000 crashes, Solomon concluded that injury severity increased at speeds exceeding 60 mph, and the likelihood of a fatal crash raised drastically for speeds over 70 mph. Joksch (1993) found that the probability of fatality for a vehicle driver in a crash increased sharply with the change in vehicle travel speed as shown in Figure 2.6. It can be seen from the figure that the fatal probability rises at 30 mph speed and is over 50 percent when the impact speed exceeds 60 mph. The probability of a driver being killed at 50 mph is 15 times that of the fatal probability at 25 mph. The fatal probability curve from the research by O'Day and Flora (1982) was also shown for comparison. The difference in the curves was attributed to vehicle quality, seat-belt use and emergency medical care. Research conducted by O'Donnell et al. (1996), and Kockelman et al. (2002) also showed the strong relationship between vehicle travel speed and injury severity level.

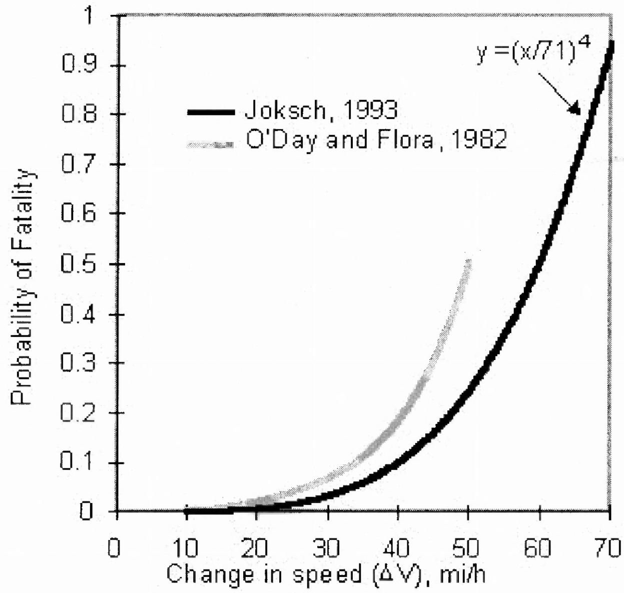

Figure 2.5 Effect of change in speed on probability of fatality.
(Source: Joksch 1993)

The relationship between vehicle speed and injury severity sustained by pedestrians and bicyclists is critical since they are more vulnerable road users compared with vehicle occupants. Zegeer et al. (2002) showed that speeding played an important role in pedestrian injury severity in vehicle-pedestrian crashes. The authors also showed that the probability of a pedestrian fatality was 0.85 when a pedestrian was struck by a vehicle at 40 mph speed, the probability reduced to 0.45 at 30 mph, and at 20 mph vehicle speed, the probability decreased sharply to only 0.05. The result indicated that the probability of serious injury level increases drastically with increased vehicle travel speed. This conclusion was also supported by other studies conducted by Pasanen and Salmivaara (1993), Leaf and Preusser (1999), Pharaoh and Russell (1991), Proctor (1991), Anderson et al. (1997), Ivan et al. (2001), Davis (2001), and Davis et al. (2003).

Since children are much more vulnerable in crashes, some of the studies were focused on injury severity of crashes involving children pedestrian. Jacobsen et al. (2000) conducted a research on child pedestrian injuries on residential streets. A joint exponential model of the pedestrian injury risk was applied to evaluate five variables, including vehicle speed, vehicular volumes, parking vehicles, total pedestrians and multiple-family housing. The results showed that vehicle speed was the most important factor for pedestrian injuries. The risk of pedestrian injury at 30 mph was shown to be 7.6 times that of pedestrian injury at 20 mph speeds.

Pitt et al. (1990) also studied the pedestrian injury severity in children. The Pedestrian Injury Causation Study (PCIS) data, which was obtained by several survey teams gathering pedestrian injuries data from five U.S. cities police report between September 1977 and March 1980, was used for the research. The authors selected 1035 urban pedestrian injuries that involved youth below 20 years of age. By using the Injury Severity Score (ISS) to denote pedestrian injury severity, the results illustrated that vehicle speed was strongly related to injury severity. The Injury Severity Score (ISS), which takes a value from 0 to 75, is an anatomical scoring system providing an overall score for patients with multiple injuries. Each injury is represented by an Abbreviated Injury Scale (AIS) score and responds to one of six body regions including head, face, chest, abdomen, extremities including Pelvis, and external. The ISS is then obtained from the sum of the squares of the highest AIS score in each of the three most severely injured body regions. For example, the mean ISS was 4.16 for vehicle speeds less than

20 mph, and 11.06 for vehicle speeds 30 mph or more. The research showed that 20 percent of children were hit by vehicles with speeds of more than 30 mph, and the victims sustained more serious injuries compared with those struck by lower speed vehicles.

In addition, several studies showed relationship between vehicle travel speed and injury severity sustained by bicyclists when involved in crashes. Landis (1994) developed a model to predict bicyclists' risk when they shared the roadway with motor vehicles. The research used the IHS (Interaction Hazard Score) to evaluate roadway safety. IHS means bicyclists' perception of the hazard of sharing roadway with motor vehicles. The result indicated a strong relationship between vehicle speed and bicyclist's safety. Davis (1987) conducted a research to identify significant factors impacting bicyclist safety. The research was based on 29 bicyclists' perceptions of eight routes in the Atlanta, Georgia metropolitan area. Davis' analysis indicated that traffic volume and speed played the most important role in identifying bicyclist suitability, which used bicycle safety index rating (BSIR) to denote roadway conditions for bicycle operation.

2.2 Criteria for Setting Speed Limits

This research is aimed to develop a procedure for setting speed limits for shared roadways based on pedestrian/ bicyclist injury severity. Other criteria for setting speed limits, however, must be taken into account to establish optimal speed limit. Therefore, it is necessary to review the criteria used by various states, organizations and agencies for setting speed limits.

Speed limits generally represent the maximum safe and reasonable speed on roadways in good traffic and roadway conditions. Therefore, a reasonable speed limit should provide drivers with enough time to take actions to slow down or stop vehicles in emergency conditions so that potential crashes can be avoided. In general, jurisdictions such as the state, counties and cities that have control over a roadway have the authority to set speed limit for that roadway. Setting speed limit on a particular roadway, however, is primarily based on traffic engineering study or survey. The following sections describe a review of the criteria for setting speed limits in various countries.

2.2.1 Definition of Speed Limit

There are several kinds of speed limits and these are stated as follows (TRB, 1998):

1. Statutory Speed Limits: statutory speed limits are the speed limits specified by state motor vehicle laws and are determined for specific categories of streets and highways. These limits can be changed in terms of an engineering study.
2. Posted Speed Limit: the posted speed limit is a numerical value conveyed to drivers using regulatory sign. It is typically set based on an engineering study and may be a different speed limit than the statutory value.
3. Prima Facie Speed Limit: the prima facie speed limit is the speed limit above which motorists are possibly charged with driving unlawfully. Approximately one-third of all

states in U.S. use prima facie speed limits or both prima facie and absolute speed limits. Absolute speed limits are alternate speed limits to the prima facie limits.

4. Absolute Speed Limit: the absolute speed limit is a numerical value above which is always regarded as unlawful regardless of roadway or environmental conditions. Approximately two-thirds of the states use absolute speed limits with prima facie speed limits as alternatives.

5. Differential speed limits: differential speed limits specify different speed limits for different types of vehicles. It is based on the rule that large trucks need much longer stopping distances than cars.

2.2.2 MUTCD Guidelines of Setting Speed Limits

The Manual of Uniform Traffic Control Devices (MUTCD) presents in Section 2B.11 guidance on setting speed limits. The guidance recommends the 85th percentile speed of free flow traffic to be the posted speed limit, rounded up to nearest 5mph increment. Also, the guidance provides possible factors to be considered for setting speed limits. The factors include (Source: MUTCD, 2000):

- Road characteristics, shoulder condition, grade, alignment, sight distance;
- The pace speed;
- Roadside development and environment;
- Parking practices and pedestrian activity; and

- Reported crash experiences for at least a 12-month period.

2.2.3 Other Speed Limit Setting Guidelines

In 1998, the Transportation Research Board (TRB) published "*Special Report 254: Managing Speed*". The main objectives were to review the current practice for setting and enforcing speed limits on all roads rather than just on major highways, to provide state and local governments with guidance on appropriate methods of setting speed limits, and to describe related enforcement strategies. The report identified four primary methods of setting speed limits. These methods are stated as follows:

Statutory speed limit: A statutory speed limit is one established by the legislature. This kind of limit can be determined by federal, state or local government. In the process of determining the speed limit, many other factors such as design speeds, crash data, vehicle travel speeds, and traffic congestion are considered. In addition, the statutory speed limit can be changed based on engineering study. The 55 mph of National Maximum Speed Limit (NMSL), for instance, was established in 1973 in response to energy crisis to reduce energy costs. However, there was a repeal of the NMSL of 55 mph in 1995, which allowed States to set appropriate speed limits on major highways because the public was no longer concerned about energy cost at that time.

Optimum speed limits: Optimum speed limits are based on the optimal level from a societal perspective. The optimum speed can be determined by obtaining the minimum point of total cost, which includes costs such as vehicle operation cost, crash cost, travel time cost and other social costs. Although this method is appropriate for setting speed limits for different road types, it has never been used in practice due to the difficulty of quantifying key variables.

Engineering study method: An engineering study method sets speed limit in terms of 85^{th} percentile speed. The speed limit may be adjusted based on other factors such as crash experience, roadside development, roadway geometry, and maximum speed limits set by statute or local ordinance. For example, on urban roads, particularly on urban residential streets, the public will be concerned more about pedestrian safety, property access rather than travel efficiency. Therefore, setting speed limits based on 85^{th} percentile speed is no longer appropriate.

Expert system-based approach: An expert system-based approach uses expert system to propose speed limits. The expert system applies computer programs to imitate an expert's thought processes to solve problems in the procedure of setting speed limits. The expert system not only takes into account all the factors included in the engineering study method, but also provides more explicit factors and decision rules in the process of determining speed limits. The system seems to be most appropriate for roads where the 85^{th} percentile speed is regarded as not suitable for setting speed limits.

Other approaches: Other approaches for setting speed limits include basic law limits, which means "vehicles shall be driven in a careful and prudent manner, depending on the conditions at the time and place of operation" (TRB, 1998). Variable speed limits are also the type of speed limits, which provide drivers with guidance on appropriate maximum and minimum speed limits based on actual traffic and roadway conditions.

2.2.4 Speed Limit Criteria in States

As each state has authority to establish speed limits on roadways within the state, there are various speed limits in different states based on different criteria. The following sections introduce criteria of setting speed limits in New Jersey and the other similar States. Since the data used in this research are obtained from NJDOT accident database, it is necessary to review the criteria for setting speed limits in New Jersey. The criteria in other two states, Minnesota and Florida, are reviewed to show comparisons among various states.

2.2.4.1 New Jersey. The *New Jersey Permanent Statutes* Title 39 Motor Vehicles and Traffic Regulations provide guidance on setting speed limit in New Jersey. Title 39:4-98 states that unless a lower speed is specified, the prima facie rate of vehicle speed should not exceed (Source: New Jersey Permanent Statutes):

a) Twenty-five miles per hour, when passing through a school zone during recess, when the presence of children is clearly visible from the roadway, or while children are going to or leaving school, during opening or closing hours.

b) Twenty-five miles per hour in any business or residential district, and thirty-five miles per hour in any suburban business or residential district.

c) Fifty miles per hour in all other locations, except as otherwise provided in the "Sixty- Five MPH Speed Limit Implementation Act".

These speeds can be changed on the basis of an engineering and traffic study, which shows that different speed limits should be set under various conditions. Also, the statutes state that speed limits must be approved by the Commissioner of Transportation after an investigation.

The 85th percentile speed, which is the speed that 85 percent of motorists drive at or below, has been used as a primary factor for setting speed limits by many agencies, including the New Jersey Department of Transportation (NJDOT). However, when the 85th percentile speed is used as the most important factor in the process of setting speed limits, motorists are assumed to decide the appropriate travel by themselves, and the 85^{th} percentile speed is regarded as a reasonable safe speed for the roadway (Fitzpatrick et al., 1997). In addition, some other studies have shown that the 85^{th} percentile speed may be larger than the design speed of a roadway. Although these limitations exist, the 85^{th} percentile speed is still regarded by both agencies and researchers as one of the most important factors for setting appropriate speed limits.

In New Jersey, the engineering study conducted to establish the most appropriate speed limit includes:

- Radar checks, if possible, for 100 vehicles in each direction for each particular zone along with a sketch showing the location of the unmarked car and direction of the radar beam.
- Data showing the 85^{th} percentile speed of the above checks.

- Crash data for the latest available year.
- A description of the roadway characteristics including width, curbing, sidewalks, shoulders, adjacent land use, parking restrictions, school locations and areas of pedestrian activity.
- Ball banking data, if possible, for all curves along the roadway to determine the advisory speed to be utilized with warning signs.
- Certified Ordinance (County roadway) (Municipal roadway) with the speed limit listed in zones (beginning and ending limits within each zone) and with School Zone speed limits included if applicable. [Promulgated pursuant to N.J.S.A. 39:4-8(b)].
- A statement of the reasons the above data was unable to be submitted.
- A statement of the reasons for the engineer's decision.

2.2.4.2 Other States. Similar to the State of New Jersey, several other States, which are also located in the northeast coast area of the USA, set speed limits on various roadways. These States include Connecticut, New York, and Pennsylvania. For example, Connecticut sets speed limits as follows (NHTSA, 2001):

- 65 MPH on multiple lane, limited access highways which are suitable for such a speed limit
- 55 MPH upon other highways
- 50 MPH for a school bus on a divided limited access highway
- 40 MPH for a school bus on all other highways

New York State sets speed limits as shown below (NHTSA, 2001):

- 65 MPH on parts of certain designated highways
- Towns may establish maximum speed limits less than 55 MPH on roads within their exclusive jurisdiction.

- Cities and villages may establish maximum speed limits less than 55 MPH on roads within their exclusive jurisdiction.
- A city or village may establish maximum speeds of not less than 15 MPH on certain private driveway or parking areas
- Other local authorities or school districts may establish speed limits less than 55 MPH on driveways or parking fields under their jurisdiction

In addition, a local government may be prohibited by the State Department of Transportation from establishing maximum speed limits on certain designate State maintained highways.

Speed limits set by the State of Pennsylvania are shown as follows (NHTSA, 2001):

- 65 MPH on certain interstate highways and freeways
- 55 MPH on other highways
- 35 MPH in urban districts
- 15 MPH in a school zone

Based on engineering and traffic investigations, the State or a local government may increase or decrease the speed limits on the highways within their jurisdiction. Such speed limits may be varied under different weather conditions and other factors bearing on safe speeds (NHTSA, 2001).

2.3 Optimal Speed Limit

Studies have been conducted proposing the use of optimal speed limits from a societal perspective rather than from individual drivers' viewpoint. Individual drivers do not always recognize the risks imposed on others by their choice of driving speeds. Also, they do not take into account such speed-related costs as air pollution costs, fuel consumption costs. The optimal speed for an individual driver is therefore different from the optimal speed for a social community, and thus, calculating social optimal speed limits appears to be more comprehensive than calculating individual optimal speed limit only.

Oppenlander (1962) proposed a method to express costs per mile of travel as a function of speed. The total costs consisted of four categories, including vehicle operation cost, time cost, crash cost, and service (comfort and convenience) cost. In that study, cost curves were developed by economic studies of vehicular travel on two-lane and multilane highways, in various traffic areas under a set of travel conditions and for different types of vehicles. The optimal speed was then determined as the minimum point on the total cost curve. The point represents the minimum social cost of highway transportation based on a particular set of conditions.

Marcellis (1962) used Oppenlander's approach to obtain optimal speed limits for passenger cars and commercial vehicles on two and four lane roadways in urban and rural areas on day and at night. The result indicated that optimal speeds, which minimized the total cost, could be determined for each of above conditions. For instance, there was an 11 mph difference in optimal speed limits between for passenger cars and for commercial vehicles, and the optimal speed for passenger cars in rural area was 50 mph while in urban areas it ranged from 29 mph to 41 mph.

Jondrow (1982) also used the above approach to obtain the social optimum speed. In the research, the optimal speed for individual drivers was first determined by selecting the intersect point of marginal benefit and marginal cost for speed. The result showed that the optimal speed was impacted by such factors as the value of time, the value of life, gasoline price, the increased gasoline use, and fatality rate variation per mile change of speed. Then, the optimal speed was adjusted to be the social optimal speed by taking into account external costs. The model for the social optimal speed developed in that research was expressed as follows,

$$S_s = V_T^{0.5}[P_G c + V_L(b + b')]^{-0.5} \tag{2.1}$$

Where,

S_s: social optimum speed

V_T: value of time ($/h)

P_G: the price of gasoline

V_L: the amount necessary to compensate a driver for an increase in the probability of a fatal crash

c : the increase in gasoline use per mile as speed increase 1 mph.

b : the increased probability per mile on driver of a fatal crash as speed increase 1mph

b': the increased probability per mile on other people of a fatal crash as speed increase 1 mph

2.4 Speed Limit and Total Cost

In this dissertation, total cost is defined as the summation of crash cost, travel time cost, fuel cost, and emissions cost. Each of the costs is described in following section.

2.4.1 Crash Cost

Speed has been proved by previous studies to be strongly related to crash severity. Therefore, it is obvious that decreasing vehicle speeds can reduce injury severity sustained by both vehicle occupants and pedestrians/bicyclists who are involved in crashes. As a result, crash cost can also be reduced when speed is reduced.

The Federal Highway Administration (FHWA) determined comprehensive crash costs by using respectively the KABCO and abbreviated injury scale (AIS) shown in Tables 2.6 and 2.7.

Table 2.6 FHWA Comprehensive Crash Costs by KABCO Scale Injury (1994 & 2000 Dollars)

Injury Severity	Description	Cost (1994 $)	Cost (2000 $)*
K	Fatality	2,600,000	3,366388
A	Incapacitating injury	180,000	233,100
B	Evident injury	36,000	46,620
C	Possible injury	19,000	24,510
PDO	Property damage only	2,000	2,590

Source: FHWA (1994), * denotes the value is calculated based on fatality value change in AIS scale

Table 2.7 FHWA Comprehensive Crash Costs by AIS Scale Injury (1994 & 2000 Dollars)

Injury Severity	Description	Cost (1994 $)	Cost (2000 $)
AIS 6	Fatality	2,600,000	3,366,388
AIS 5	Critical injury	1,980,000	2,402,997
AIS 4	Severe injury	490,000	731,580
AIS 3	Serious Injury	150,000	314,204
AIS 2	Moderate injury	40,000	157,958
AIS 1	Minor injury	5,000	15,017

Source: FHWA (1994, 2000)

The comprehensive costs shown in Tables 2.6 and 2.7 include direct costs related to property damage, emergency medical services (EMS), medical treatment, lost productivity, and insurance payouts, and indirect costs consisting of insurance premiums and automobile safety features.

2.4.2 Travel Time Cost

In addition to traffic safety, speed also influences vehicle travel time, which is an important factor for drivers to choose appropriate travel speeds. An increase of travel speed on a specific segment results in a decreased travel time since the travel time is defined as the travel speed divided by the segment length under free flow condition.

Travel time cost is defined as the product of travel time (hour), value of travel time (US$/hour), and average vehicle occupancy (AVO). Studies have been conducted to obtain travel time value. In their study on benefit-cost evaluation of an electronic toll collection system, Li et al. (1999) showed that the average time value for vehicle occupants in California was $9.73 per hour in 1995, with a vehicle mode share being 5.11 percent for trucks and 94.89 percent for automobile and buses, and the average vehicle occupancies remained unchanged over the study period. The value of time in the above study was originally obtained from the hourly value in the Highway Economic Requirement System (HERS), which is a computer model employed by the U.S. Department of Transportation, and then the value was adjusted in terms of inflation rate and the mode share of vehicles. In addition, the authors assumed that average vehicle occupancies were the same as the national average with the values of 1.8 for auto, 1.1 for truck, and 20 for bus.

According to a study conducted by Levinson in 1994, the value of time for vehicle occupants in the State of Massachusetts was about $12 per hour in 1993 with the assumption that average annual household worker worked for 2300 hours per hour, and that the estimation of median household income in the State was $34,662.

A study conducted by Texas Transportation Institute (TTI, 1999) titled 'The Urban Mobility Report', quantified urban mobility in terms of congestion cost for 68 major urban areas in USA, including the NY-NJ-Philadelphia area. TTI used the national average wage rate of $12.40 in 1999 as the value of time in the study to calculate congestion cost for NY-NJ-Philadelphia area. Later, the National Center for Transportation and Industrial Productivity (NCTIP) at New Jersey Institute of Technology (NJIT, 2001) conducted a study on mobility and costs of congestion in New Jersey. The study used county-based wage data in the year 2000 as the value of time to evaluate congest cost for each county in New Jersey. The wage rates ranged from $11.75 for Cumberland County to $26.87 per hour for Somerset County. In this dissertation, however, the selected roadways are across the State, the average wage rate of $18.79 in the year of 2000 in New Jersey is then used as the value of time to obtain travel time cost in order to better reflect New Jersey conditions. In addition, average vehicle occupancy of 1.25, a value assumed for all roadways in New Jersey in the 2000 NJIT study, is also used in this dissertation.

2.4.3 Emissions Cost

Speed has been proved to be a factor impacting vehicle emissions, these emissions contribute to the pollution of the atmosphere. In general, emissions such as volatile organic compounds (VOCs) and carbon monoxide (CO) are highest in low-speed, congested conditions and rise again in high speed, free-flow driving conditions. Greater engine power demands at high speeds produce more VOC and CO emissions, but it is unclear either about the exact speed that this situation occurs or the quantity of extra emissions produced. Emissions of oxides of nitrogen (NOx) increase gradually at speeds well below free-flow freeway speeds, but it is also uncertain about what speed the increase begins and the rate of increase (TRB, 1995).

Studies have been conducted to estimate air pollution cost. For example, the unit costs of air pollutants in year 2000 A$ (Australia Dollar) are stated by Cameron (2003) as follows:

- Carbon monoxide $ 0.002 per kilogram
- Hydrocarbons $ 0.44 per kilogram
- Nitrogen oxides $1.74 per kilogram
- Particulates (PM10) $13.77 per kilogram
- Carbon dioxide $ 0.022 per kilogram

Wang et al. (1995) applied two methods including control cost method and damage value method to calculate unit emission cost for 17 cities in U.S. The result showed unit emission values of air pollutants including NOx, ROG (reactive organic gases), CO, PM10 (particulate matter less than 10 microns) and SOx, and there were different values in different cities. For example, the emission values obtained from the damage value method had a range from $2840 to $6890 per ton for NOx, $1350 to $3540 per ton for ROG, $2960 to $10840 per ton for PM10, and $2210 to $3600 per ton for Sox. In addition, FHWA (1997) provides air pollution costs estimates as shown in Table 2.8. Li et al. (1999) provided unit cost of pollutants in their study. Unit costs of Nox, HC, and CO were $1.28/kg, $1.28/kg, and $0.0063/kg (1995 Dollars), respectively. In this research, unit cost of pollutants provided by Li et al. was used and then adjusted to the year 2000 dollars because only this research provided unit costs of the three emissions obtained from CORSIM simulation. As for the problem of different unit costs in various areas, the result of this dissertation shows that air emission cost only take a very small proportion, say 0.05%, of total cost, then the impact of area difference on unit cost estimation can be ignored.

Table 2.8 Air Pollution Costs

Vehicle Class	Total ($ 1990 Million)	Cents per Mile
Automobiles	$20,343	1.1
Pickups/Vans	$11,324	2.6
Gasoline Vehicles >8500 Pounds	$1,699	3.0
Diesel Vehicles > 8500 Pounds	$6,743	3.9

Source: FHWA (1997)

2.4.4 Fuel Consumption Cost

Similar to the impact of speed on emissions, vehicle speed also greatly influences fuel economy. Davis (1994) showed that fuel consumption could be expressed as a function of vehicle speed. Under certain conditions, such as steady state and cruise-type driving conditions, fuel efficiency peaks at 35 to 45 mph and then drops at higher speeds. Also, fuel efficiency is reduced at lower speeds due to engine friction, tires and accessories (e.g., power steering and air conditioning) (TRB, 1995). However, in a study conducted by Davis in 1997, the speed with best fuel efficiency was adjusted to 55 mph under steady state, cruise-type driving conditions (TRB, 1998).

This dissertation used the fuel cost $1.46 per gallon for the year of 2000 based on the 2000 NJIT study, which obtained the fuel price from New Jersey from AAA website.

2.5 Existing Crash Incidence and Injury Severity Models

Models such as linear regression model, ordered probit model, logistic regression model, have been used to predict either probability of crash incidences or injury severity caused by crashes. In the following sections, several models for crash frequency prediction or injury severity prediction and their applications are briefly introduced.

2.5.1 Empirical Crash Frequency Models

Several empirical crash probability prediction models developed by European experts were based on the crash experience data, and showed the relationship among the number of pedestrian-vehicle crashes, vehicle volume and pedestrian volume.

The Swedish model (Brude, 1998) is stated as follows:

$$N\_Crash = (0.00000734) * (Vehs)^{0.50} * (Peds)^{0.72} \tag{2.2}$$

Where

N_Crashes: Number of Pedestrian Crashes per Year

Vehs= number of incoming vehicles a day, and

Peds= number of passing pedestrians a day.

The English model (Maycock, 1984) has a similar function as the Swedish model, it states as follows,

$$N\_Crash = (0.028) * (Vehs * Peds)^{0.53} \tag{2.3}$$

Where

Vehs= number of incoming vehicles a day, and

Peds= number of passing pedestrians a day.

Since pedestrian volume is required in the empirical models above, the models cannot be used in this research because pedestrian volume is not available in an existing database. Also, it is impossible in this research to collect pedestrian volume data due to the large number of roadways and even larger number of crash locations where data would need to be collected. Therefore, Poisson and negative binomial regression model are used in this research to show the relationship between crash probability and speed limit.

2.5.2 Poisson and Negative Binomial Crash Frequency Model

Poisson and negative binomial model have been used in many studies to develop accident prediction model (Miao et al., 1993, Miao, 1994). Miao et al. (1993) used Poisson model to determine relationships between vehicle crashes and highway geometric design. The author indicated Poisson model was appropriate in developing the relationships when the vehicle accident data were not significantly overdispersed, namely, there did not have a great difference between the mean and the variance of data.

Later, Miao (1994) conducted a study to evaluate Poisson and negative binomial regression model in the process of developing relationship between truck accidents and geometric design of road sections. The result showed that Poisson model could be used as initial model to develop the relationship, and if there existed overdispersion of crash data, both negative binomial model and zero inflated Poisson models could be used to develop the relationship.

Schneider et al. (2001) applied negative binomial models to show the impact on pedestrian crashes of exposure, roadway, and land use factors. Poisson models were also developed for comparison although the difference of the mean and variance were large, indicating the negative binomial models were more appropriate. Significant variables found to be significant in the study included segment length, pedestrian volume, marked crosswalk, the number of bus stops, and crash location.

2.5.3 Logistic Injury Severity Model

The injury severity levels used in this research, which follow a KABCO scale, are regarded as ordered outcomes. In a KABCO scale, K represents killed, A stands for incapacitating injury, B represents moderate injury, C means complaint of pain, and O stands for property damage only. Therefore, both ordered logit model and ordered probit model, which are introduce in this section and next section, can be used to develop the relationship between injury severity and speed limit.

According to Hosmer (2000), the goal of logistic regression modeling is to evaluate the relationship between a dependent variable and various independent variables. The difference between logistic regression model and linear regression modeling is that the dependent variable in a logistic regression model is binary or ordered while in linear regression model it is continuous.

Logistic regression model uses the logit transformation of the probability of an event's occurrence as a linear function of a set of independent variables. For an ordered logistic model with a dependent variable that can be categorized into i levels, the proportional odds model, which is the most commonly used ordered logistic regression model in practice, takes the following form:

$$
\begin{aligned}
&g_1(X) = \log it(\phi_1(X)) = \log\frac{\phi_1(X)}{1-\phi_1(X)} = \beta_1 + \beta X \\
&g_2(X) = \log it(\phi_1(X)+\phi_2(X)) = \log\frac{\phi_1(X)+\phi_2(X)}{\phi_3(X)+\phi_4(X)+..+\phi_i(X)} = \beta_2 + \beta X \\
&. \\
&. \\
&g_k(X) = \log it(\phi_1(X)+\phi_2(X)+...+\phi_k(X)) = \log\frac{\phi_1(X)+\phi_2(X)+...+\phi_k(X)}{\phi_{k+1}(X)+\phi_{k+2}(X)+...+\phi_i(X)} = \beta_k + \beta X \\
&\phi_1(X)+\phi_2(X)+...+\phi_{i+1}(X) = 1
\end{aligned}
\tag{2.4}
$$

Where $\phi_1(X), \phi_2(X), ...\phi_i(X)$ represent the probability of the dependent variable Y falling in correspond categories denoted by 1,2 …i. β_k denotes the intercepts, and β denotes the vector of coefficients.

As an effective analytical tool, logistic regression model has been applied in previous research to develop relationship between various outcomes and a set of independent variables. For example, McMahon et al. (1999) applied conditional and binary logistic model to examine if various socioeconomic and geometric factors impact the probability of a site being a potential crash site. Kim et al. (1996) developed a binary logistic model to predict the probability of drivers being at fault in vehicle-bicycle crashes. Ossenbruggen et al. (2001) also used logistic modeling to determine factors that significantly impact the likelihood of crashes as well crashes with injuries. Dissanayake et al. (2002), and O'Donell et al. (1996) applied logistic model to identify variables influencing driver injury severity in vehicle-fixed object crashes, and crashes between vehicles.

2.5.4 Ordered Probit Injury Severity Model

In this research, ordered probit model is used to develop injury severity models. A detailed introduction to ordered probit model will be given in chapter 3.

A number of studies had been conducted using ordered probit model to determine the relationship between injury severity and various factors. Klop et al. (1999), and Ivan et al. (2001) used ordered probit model to study the effect of roadway and environmental variables on injury severity of pedestrians and bicyclists involving in crashes with motor vehicles. The variables included straight grades, curved grades, darkness, fog, and speed limit. The result in Klop's research showed such factors as grades, darkness, weather, speed limit, AADT, interaction of speed limit and shoulder width significantly impact bicyclist injury severity. Ivan's research indicated that variables like roadway width, vehicle type, driver alcohol involvement, pedestrian age, and pedestrian alcohol involvement significantly impact pedestrian injury severity.

Duncan et al. (1998) also applied ordered probit model to evaluate the effects of various factors on injury severity of vehicle occupants involving in crashes between passenger cars and heavy trucks. Factors that impacted injury severity, including speed differentials, speed limit, grade, light condition, wet condition, were determined, and countermeasures based on the results were recommended.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this research, injury severity models for both urban and rural areas are developed to predict the injury severity sustained by a pedestrian or bicyclist involved in a collision with a motor vehicle, and by drivers or passengers involved in motor vehicle crashes. Injury severity is regarded as the dependent variable with five injury levels as used on the New Jersey State police report. Speed limit, road type, median type, median width, annual average daily traffic (AADT), number of lanes, pavement width, and shoulder width, are selected as independent variables. To develop appropriate injury severity models, specific criteria are chosen to test the significance of the independent variables so that significant variables are kept in the model and less significant variables are eliminated. Also, crash frequency prediction models predicting the number of crashes for urban and rural areas are developed separately, including prediction models for crashes between motor vehicles, and models for crashes between motor vehicles and pedestrians or bicyclists. As the dependent variable, the crash frequency is a function of independent variables including speed limit, AADT, pavement width, road type, median type, number of intersections on the roadway segment, and number of signalized intersections on the segment.

3.2 Methodology Flow Chart

The optimal speed limits developed in this research are defined as the speed limits that minimize the total cost associated with the speed limit including the costs of motor vehicle crashes and vehicle-pedestrian/bicycle crashes. The approach for determining the optimal speed limit is similar to what proposed by Oppenlander (1962). A total cost model is developed to express cost per mile of travel as a function of posted speed limit. The total cost includes crash cost, travel time cost, fuel consumption cost, and vehicle emissions cost. Each of these costs varies with the posted speed limit, and cost curves were obtained based on the relationship between costs and speed limits. The optimal speed limit is then determined as the minimum point on the total cost curve. This minimum total cost indicates the minimum social cost of transportation based on a particular set of conditions. Oppenlander focused his study on rural two and four-lane highways where pedestrian and bicyclist activities were rare. This research attempts to obtain social optimal speed limits in both urban and rural areas with shared roadways. Figure 3.1 shows the process of obtaining the optimal speed limit. As it can be seen from the figure, the optimal speed limit is based on the comparison of total cost, which is the combination of crash cost, travel time cost, fuel cost, and emissions cost. The following sections introduce the method and procedure for the model's development.

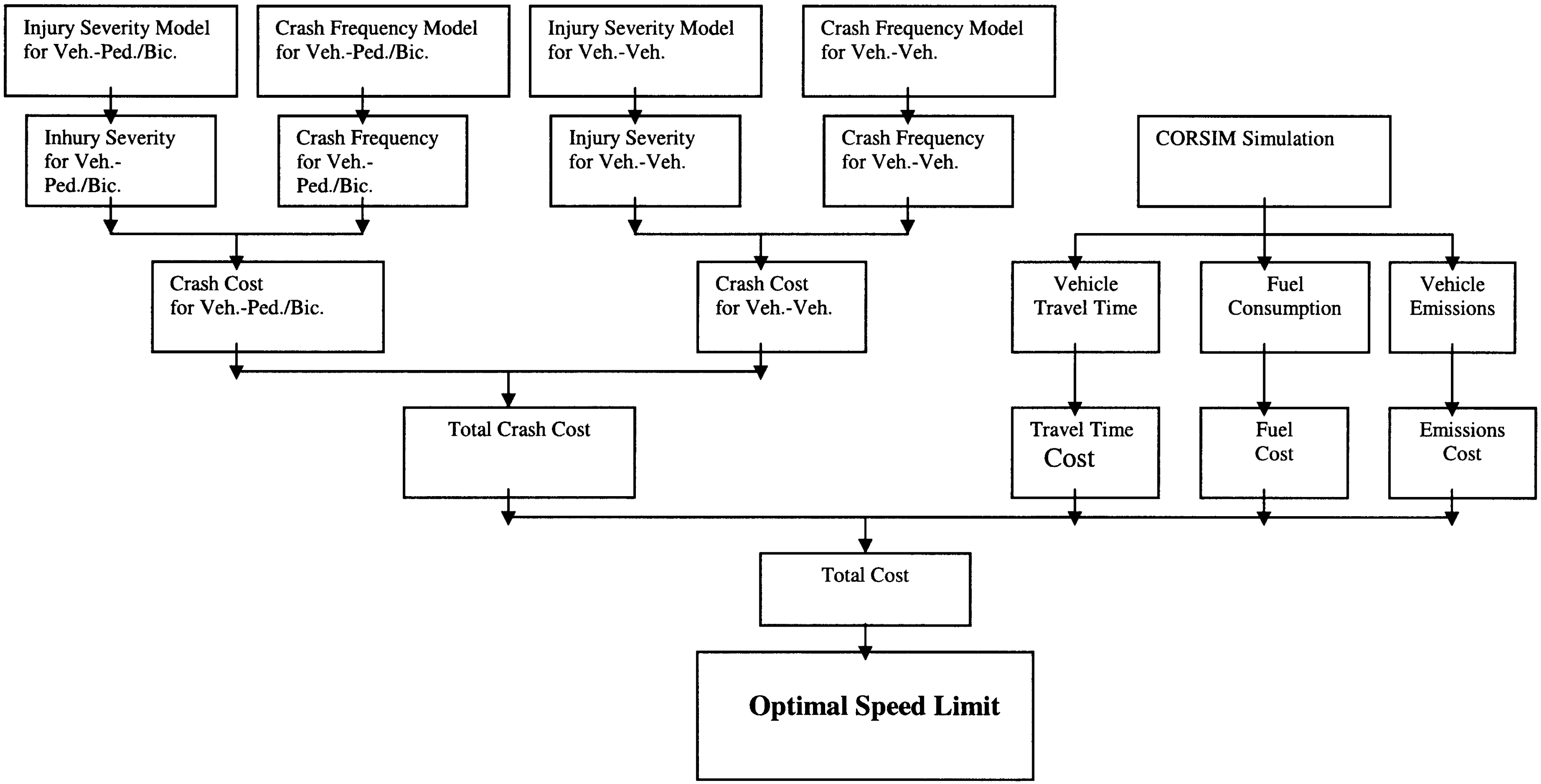

Figure 3.1 Process of Obtaining Optimal Speed Limit.

3.3 Crash Cost Analysis

Calculation of the crash cost is based on the crash frequency, probability of each injury severity for victims involved in a vehicle-vehicle crash or a vehicle-pedestrian/bicyclist crash, and the unit cost for each injury severity level. The probability of injury severity level caused by a crash is obtained from a crash severity model developed in this research. Crash frequency is provided by a crash prediction model also developed in this research. In addition, the unit cost of each injury severity level is provided by Federal Highway Administration (FHWA) guidelines for each injury severity level as shown in the previous chapter.

3.3.1 Ordered Probit Crash Severity Model

In this research, an ordered probit model is used to obtain the probability of injury for each severity level sustained by drivers, passengers, or pedestrians/bicyclists involved in motor vehicle crashes. An ordered probit model is a multivariate model that can describe relationships between a dependent variable and a set of independent variables. The dependent variable in an ordered probit model is an ordinal response using integers to represent an ordered sequence. By analyzing the marginal effects of the independent variables, ordered probit models have the ability to determine whether the independent variables significantly influence the dependent variable, namely, the injury severity sustained by vehicle occupants when a crash occurrs. In general, an ordered probit model describing injury severity takes the form:

$$Y^* = bX + \varepsilon \tag{3.1}$$

where Y^* = an unobserved variable measuring the risk of injury,

X = a vector of non-random independent variables,

β = a vector of unknown coefficients, and

ε = a random error term (assumed to follow a standard normal distribution).

The observed and ordered injury severity Y, is given by:

$$Y = k \text{ If } \mu_k \leq Y^* \leq \mu_{k+1} \text{ for } k = 0,1,2,3,4 \tag{3.2}$$

where k denotes the ordered category of injury severity, and μ_k are the estimated thresholds. Injury severity is regarded as the dependent variable with five levels in this research including: Y = 4 if the accident victim is killed; Y = 3 if victim suffers an incapacitated injury; Y = 2 if victim is moderately injured; Y = 1 if victim has a minor injury; and Y =0 represents property damage only crashes. Therefore, the dependent variable can be expressed as follows:

$$Y = \begin{array}{ll} 0 \text{ if} & \left\{\begin{array}{ll} -\infty \leq Y^* \leq \mu_1 & \text{(property damage only)} \\ \mu_1 < Y^* \leq \mu_2 & \text{(minor injury)} \\ \mu_2 < Y^* \leq \mu_3 & \text{(moderate injury)} \\ \mu_3 < Y^* \leq \mu_4 & \text{(incapacitating injury)} \\ \mu_4 < Y^* \leq +\infty & \text{(killed)} \end{array}\right. \\ 1 \text{ if} & \\ 2 \text{ if} & \\ 3 \text{ if} & \\ 4 \text{ if} & \end{array}$$

where μ_k represent the injury severity level thresholds estimated by the model.

Figure 3.2 shows the relationship between the unobserved injury variable Y^*, and the observed injury severity Y.

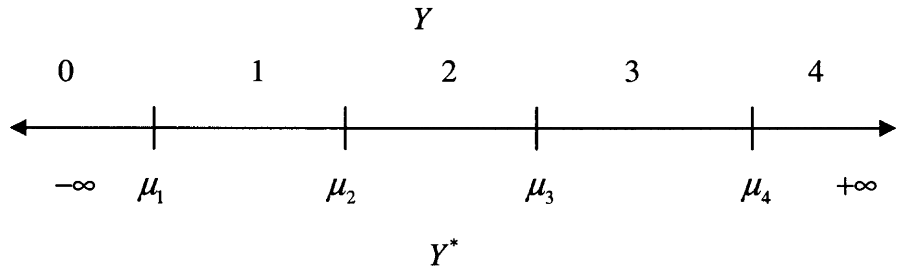

Figure 3.2 Relationships between unobserved and observed injury severity.

Therefore, the probabilities of the ordered categories are as follows:

$$p(Y=0)=\phi(-\beta X) \tag{3.3}$$

$$p(Y=1)=\phi(\mu_1-\beta X)-\phi(-\beta X) \tag{3.4}$$

$$p(Y=2)=\phi(\mu_2-\beta X)-\phi(\mu_1-\beta X) \tag{3.5}$$

$$p(Y=3)=\phi(\mu_3-\beta X)-\phi(\mu_2-\beta X) \tag{3.6}$$

$$p(Y=4)=1-\phi(\mu_3-\beta X) \tag{3.7}$$

where $p(Y=k)$ denotes the probability of an injury severity falling in category k, and ϕ denotes the cumulative distribution function of the standard normal distribution.

Since the dependent variable in an ordered probit model is not continuous, the ordinary least square (OLS) estimation method is not suitable for obtaining coefficients, thus the Maximum Likelihood Estimation (MLE) is used to solve this kind of problem. MLE is a statistical method for estimating the coefficients of the independent variables that maximize the probability of obtaining the observed set of data. A likelihood function must be built to describe the probability of the observed data as a function of a set of independent variables.

Let $f_k(X)$ be a function of the unknown parameters, $\theta=(\theta_1,\theta_2,...\theta_k)$ be the values of ordered outcomes with k levels, and $\theta_k=1$ if the dependent variable Y=k, with $\theta_i=0$ otherwise. The likelihood function for n independent observations, is given as:

$$l(\beta)=\prod_{i=1}^{n}[f_1(X_i)^{\theta_{1i}}f_2(X_i)^{\theta_{2i}}...f_k(X_i)^{\theta_{ki}}] \tag{3.8}$$

and the log likelihood is,

$$L(\beta)=\sum_{i=1}^{n}\theta_{1i}\ln[f_1(X_i)]+\theta_{2i}\ln[f_2(X_i)]+...+\theta_{ki}\ln[f_k(X_i)] \tag{3.9}$$

The parameter coefficients can be obtained by taking the first partial derivatives of $L(\beta)$ with respect to each unknown parameter, and then by setting the resulting equations to zero.

Once the parameters are estimated using the ordered probit model, significant variables that impact injury severity of vehicle occupants or pedestrians/bicyclists can be identified. Significant variables are determined using the p-value associated with each variable of the model. A variable at a 90 percent confidence level has a corresponding p-value ranging from 0 to 0.1, and is regarded in this research as significant in impacting injury severity. In addition, for continuous independent variables, positive coefficients mean more severe injury as the magnitude of the variable increases, while negative coefficients represent less severe injury as the magnitude of the variable increases. Similarly, positive coefficients of categorical variables indicate the variables would increase injury severity compared to a referral category, while negative coefficients represent decreased injury severity. For example, road type, weather condition, and light condition are categorical variables in the developed injury severity model. Whether the road is an urban principal arterial, whether there is clear weather, and whether day light condition exists are selected as previously stated referral categories for each of the categorical variables.

3.3.2 Poisson and Negative Binomial Crash Prediction Model

Various mathematical models have been used to model relationships between a dependent variable and a set of independent variables. The models discussed in this research include a Poisson model and negative binomial model.

Poisson and negative binomial models have been used in many studies to develop a crash prediction model (Miao et al., 1993, Miao, 1994). A Poisson model takes the following form:

$$P(Y = k) = e^{-\lambda} \lambda^{k} / k! \quad k = 0,1,2\ldots\ldots \tag{3.10}$$

Where

$$E(Y) = Var(Y) = \lambda = \exp(\beta x) \tag{3.11}$$

Y : Dependent variable, number of crashes

x : Vector of independent variables

β : Coefficient of independent variables

λ : The expected number of crashes

There is an assumption in the Poisson model that the variance of the data is equal to the mean. The variance in many applications, however, is likely to be greater or smaller than the mean. Therefore, the negative binomial model is also selected in this research to predict the number of crashes between motor vehicles and pedestrians or bicyclists. A negative binomial takes the following form:

$$p(Y = y) = \frac{\Gamma(y + \theta)}{\Gamma(y + 1)\Gamma(\theta)} \left(\frac{\lambda}{\lambda + \theta}\right)^{y} \left(1 - \frac{\lambda}{\lambda + \theta}\right)^{\theta} \tag{3.12}$$

$$\lambda = E(Y) = \exp(\beta x) \tag{3.13}$$

Where

θ : Estimation of the degree of overdispersion,

Γ : The Gamma function,

And the variance of Y is give by

$$Var(Y) = \exp(\beta x)(1 + \frac{1}{\theta^2}\exp(\beta x)) \tag{3.14}$$

3.3.3 Variable and Whole Model Test

The statistical program LIMDEP (version 7.0) was used in this research to develop the crash injury severity and crash frequency prediction models. Using a maximum likelihood estimation approach, LIMDEP gives coefficient results and p-values for each independent variable. The p-value provides the confidence level against the null hypothesis that the coefficient for an independent variable is zero. Smaller p-values indicate higher confidence to reject the null hypothesis. In this research, a 90% confidence level was selected to identify a significant independent variable, therefore a variable with a p-value of less than or equal to 0.1(1-90%) is regarded as significant .

After the significant variables are identified, the negative binomial model was applied to refit the model using only variables found to be significant to show the actual impact of those variables on the crash frequency. The models with only significant variables are regarded as the final models. Goodness-of-fit tests of the models were also performed to determine the significance of the models. A measure for the overall negative binomial model goodness of fit is the R square statistic, which is stated as,

$$R^2 = 1 - \frac{LL(\beta)}{LL(0)} \tag{3.15}$$

Where $LL(\beta)$ is the log likelihood with the constant only, and $LL(0)$ is the log likelihood at convergence. With a value ranging from 0 to 1, a greater R-square value means a better fit of the model.

The R-square is not appropriate for use in analyzing the ordered probit model. (O'Donnell and Connor, 1996). The first reason is that there is no generally accepted measure to test the significance of the ordered probit model, and second, previous research demonstrated potential R-square values with empirical and theoretical upper limits substantially less than one. (Cohen et al. 1986; Russell and Rives 1979). Therefore, the likelihood ratio test, which has been applied by other researchers (Zajac and Ivan, 2003), is used in this research to evaluate the significance of the ordered probit models. In this research, the ordered probit model using all the independent variables is developed. The model is then refitted using only variables found to be significant .

The likelihood ratio test compares the log likelihood of the model containing significant variables to the log likelihood of the model containing all the independent variables. The equation for the test is stated as:

$$\begin{aligned} &G = -2\ln\left[\frac{(L')}{(L)}\right] = -2[\ln(L') - \ln(L)] \\ &H_0 : \beta_k = 0 \\ &H_1 : \beta_k \neq 0 \end{aligned} \tag{3.16}$$

Reject H_0, if $G > \chi^2(q, \partial)$

Where L' denotes the likelihood with significant variables only and L represents the likelihood with all independent variables, ∂ is the selected significance level, q is the degrees of freedom, χ^2 the chi-square, and H_0 the null hypothesis, which states that additional variables beyond significant ones do not have an impact on injury severity.

To test the significance of the whole model, equation (3.17) was used,

$$G' = -2\ln\left[\frac{L(0)}{L(\beta)}\right] = -2[\ln(L(0)) - \ln(L(\beta))] \tag{3.17}$$

Where $L(0)$ denotes the likelihood with constant only and $L(\beta)$ the likelihood with significant variables.

The test statistic shown in equation (3.17) also follows the chi-square distribution and reflects the significance of the entire model using $\chi^2(q)$ to represent a chi-square random variable with q degrees of freedom. If the p-value relating to the test satisfies $P[\chi^2(q) > G] < 0.1$, which is the 90% level of significance assigned in this research, then the model is regarded as statistically significant.

3.3.4 Crash Cost Calculation

Once the crash frequency and probabilities of each injury severity level have been determined, the crash cost can be obtained as a function of the crash frequency, injury probability, and unit cost of the injury severity. The functions for determining the crash cost are as follows:

$$CC_{veh-veh} = \sum_{i=0}^{4} P(Y=i) * N\_Crash * UC_i * OP_v \tag{3.18}$$

$$CC_{veh-ped/bic} = \sum_{i=0}^{4} P(Y=i) * N\_Crash * UC_i \tag{3.19}$$

$$C_{crash} = CC_{veh-veh} + CC_{veh-ped/bic} \tag{3.20}$$

Where

C_{crash}: Total crash cost,

$CC_{veh-veh}$: Crash cost caused by vehicle-vehicle crash,

$CC_{veh-ped/bic}$: Crash cost caused by vehicle-pedestrian/bicyclist crash,

UC_i: Estimated crash cost of each injury severity as shown in Table 2.1,

$P(Y=i)$: Probability of each injury severity (i=0,1,2,3,4),

N_Crash: Number of crashes,

OP_v: Vehicle occupancy (person per vehicle).

The crash cost shown in equation (3.18) describes the crash cost for crashes involving vehicle and vehicles. The crash cost in equation (3.19) shows the crash cost for crashes involving vehicle and pedestrians or bicyclists. The total cost shown in equation (3.20) is the summation of these costs.

3.4 Operation Cost Analysis

CORSIM is used in this research to simulate the operation conditions under different speed limits. CORSIM is a microscopic traffic simulation software developed by FHWA. It consists of two traffic simulation models, one is NETSIM for surface streets, and the other is FRESIM for freeways. Both of the models have been widely used by researchers over the past 30 years. The output results of CORSIM include vehicle travel time, fuel consumption, and emissions. Therefore, the travel time cost, fuel consumption cost, and air pollution cost, can be obtained from equations (3.21), (3.22) and (3.23), respectively.

$$C_{tt} = V_t * t * OP_v \tag{3.21}$$

$$C_{fuel} = W_{fuel} * V_{fuel} \tag{3.22}$$

$$C_{emission} = W_{HC} * V_{HC} + W_{CO} * V_{CO} + W_{NO} * V_{NO} \tag{3.23}$$

Where,

C_{tt}: Travel time cost ,

C_{fuel}: Fuel consumption cost,

$C_{emissions}$: Emissions cost,

V_t: Value of time per person,

t: Vehicle travel time ,

W_{fuel}: Weight of consumed fuel,

V_{fuel}: Price of fuel,

W_{NO}: Weight of emission NO,

V_{NO}: Unit cost of NO,

W_{HC}: Weight of emission HC,

V_{HC}: Unit cost of HC,

W_{CO}: Weight of emission CO,

V_{CO}: Unit cost of CO,

Once each cost is calculated from the crash frequency prediction model, injury severity model, and simulations, the total cost can be obtained as the summation of crash cost, travel time cost, fuel cost, and emissions cost. Then, based on the comparison of total cost under various speed limits, the optimal speed limit can be determined as the speed limit with the minimum total cost. The function for total cost calculation is as shown in equation (3.24),

$$TC = C_{crash} + C_{tt} + C_{fuel} + C_{emission} \tag{3.24}$$

Where,

TC: Total cost

CHAPTER 4

MODEL DEVELOPMENT

4.1 Introduction

Using the methods introduced in chapter 3, the injury severity models and crash prediction models are developed and discussed in this chapter. The procedure for developing these models includes data collection and analysis, identification of significant variables using statistical software, and formulae for injury severity and crash prediction models.

Several models are developed for determining the crash frequency and injury severity. These models include injury severity models and crash prediction models for crashes between motor vehicles and pedestrians or bicyclists, and models for crashes between motor vehicles. In addition, separate models are developed for urban and rural roadways because of differences in geometric and traffic characteristics of these two areas, and also differences in crash frequency occurring in these areas.

LIMDEP 7.0 (Greene, 1998), a statistical package, was used to develop the injury severity and crash prediction models in this research. The software package allows the development of various dependent variable regression models such as Poisson, negative binomial, probit, logit, ordered probit, multinomial logit, nested logit, and discrete choice models. In this research, an ordered probit model is used to develop the injury severity model, and a negative binomial model is used for crash prediction since the results from the model show that the overdispersion parameter is greater than zero.

4.2 Injury Severity Model

For calculating total crash cost, it is necessary to account for all crashes occurring on the roadway, including vehicle-vehicle crashes and vehicle-pedestrian/bicycle crashes. Therefore, injury severity models for pedestrian and bicyclist injuries sustained from motor vehicles were developed. Injury severity models from injuries involving vehicle-vehicle crashes were also developed in this section. Compared to vehicle occupants, pedestrians and bicyclists are more likely to be injured when hit by a vehicle because the vehicle has significantly greater mass and in addition, vehicle occupants are protected by safety equipment installed on the vehicle such as a safety belt and an air bag. Therefore, the injury severity model for vehicle-pedestrian/bicycle crashes only accounts for injury severity of pedestrians or bicyclists.

4.2.1 Data Collection and Analysis

The crash database used to develop the ordered probit model for vehicle-pedestrian/bicycle crashes includes crashes from 1997 to 2000 obtained from the New Jersey Department of Transportation (NJDOT) accident database. The database contains all crashes including fatal, injury or property damage for all counties within the State. The accident database includes variables found on the police accident report except for the name and full address of the drivers or pedestrians/bicyclists involved in the crashes. Traffic volume and geometric data were obtained from the State's straightline diagrams. The available geometric data include information on the number of lanes, pavement and shoulder widths, posted speed limit, median type and functional classification of the roadway where the crash occurred. Field data were also collected to supplement any missing data such as geometric data for urban local streets.

The injury severity of the pedestrian or bicyclist in each crash is selected as the dependent variable for the injury severity model, and a series of independent variables, both quantitative and categorical, are listed in Table 4.1. The independent variables include posted speed limit, pavement width, number of lanes, AADT per lane, median width, shoulder width, road type, road system, road geometric characteristics, surface condition, weather condition, light condition, median type, victim age, victim gender, and vehicle type. Table 4.1 shows that most of the vehicle-pedestrian/bicycle crashes studied in this research occurred on straight highways (96.8% in urban and 93.1% in rural), on roadways with dry surface (81.5% in urban and 94% in rural), on roadways without median (82.7% for urban and 89.7% for rural), during clear weather conditions (85% in urban and 95.7% in rural), and during day light conditions (62.7% for urban and 63.8% for rural area). Information about geometric characteristics shows that the average posted speed limit is about 30 mph for urban roadways and about 35 mph for rural roadways. The annual average daily traffic (AADT) per lane is 6650 and 3590 for urban and rural roadways respectively. It can also be seen from Table 4.1 that the average shoulder width in rural roadways is larger than that in urban roadways, while the average pavement width is smaller in rural roadways.

Table 4.1 Model Variables Identification for Vehicle-Pedestrian/Bicycle Crash

Variable	Description	Mean Urban	Mean Rural
Y	Injury Severity as dependent variable with 5 levels		
Continue Variables			
SL	Posted Speed Limit (mph)	31.96	35.39
PV	Pavement Width (ft)	49.94	47.66
NOL	Number of Lanes	3.33	3.28
AADTPL	Average Annual Daily Traffic per lane (vpdpl), divided by 1000	6.65	3.59
MW	Median Width (ft)	0.99	1.81
SH	Shoulder Width (ft)	2.52	6.397
Categorical Variables (Referred Categories are not shown)			
UMA	=1 if road is urban minor aRt.erial; =0 otherwise	0.177	
UC	=1 if road is urban collector; =0 otherwise	0.024	
UL	=1 if road is urban local; =0 otherwise	0.021	
RMA	=1 if road is rural minor aRt.erial; =0 otherwise		0.138
RMAC	=1 if road is rural major collector; =0 otherwise		0.603
RMIC	=1 if road is rural minor collector; =0 otherwise		0.017
RSSTATE	=1 if road is state highway; =0 otherwise	0.378	0.224
RCSTRIG	=1 if road is straight; =0 otherwise	0.968	0.931
SCDRY	=1 if road is dry; =0 otherwise	0.815	0.94
WTCLEAR	=1 if weather is clear; =0 otherwise	0.850	0.957
LCDAY	=1 if day light condition; =0 otherwise	0.627	0.638
RDBNOMED	=1 if there is no median; =0 otherwise	0.827	0.897
Age65	=1 if age of victim is greater than 65; =0 otherwise	0.093	0.078
Male	=1 if victim is male; =0 female	0.622	
VT1	=1 if vehicle type is car; =0 otherwise	0.772	
PED	=1 if victim is pedestrian; =0 bicyclist	0.717	0.448

To use these crashes in the model development, it was necessary to identify the geometric and volume characteristics at the location where each accident occurred. This could not be accomplished for all bicycle and pedestrian crashes in the State due to the large number of crashes and, therefore, a subset of crashes from the pedestrian and bicycle crashes occurring between 1997 and 2000 was used in developing the ordered probit model. The subset included 902 urban and 116 rural crashes occurring on selected roadways, which cover all roadway functional classifications. Table 4.2 shows the data summary used in the study by injury level and area type. Priority in crash data selection was given to include accidents occurring on roadways identified as high crash pedestrian or bicycle locations. This was done to include as many accidents from one roadway as possible. Roadways providing data to develop this model include CR501, CR510, Rt.1, Rt.27, Rt.21, Rt.28, Rt.35, Rt.45, Rt.47, Rt.72, CR505, CR506S, CR508, CR509, CR514, CR551, CR537, CR585, CR529, CR60, and CR603 in Essex County, CR612 and CR667 in Burlington County, and CR663 in Sussex County.

As there are 902 crashes occurring in urban areas and only 116 crashes in rural areas in the subset database, causing a great difference between the crash frequencies in these two areas, and as shown in Table 4.2, injury severities sustained by pedestrians or bicyclists are more serious in rural areas. For example, the percentage of killed or incapacitated pedestrians or bicyclists is 9.25% in urban areas, while the percentage is 23.38% in rural areas. Therefore, it is necessary to separate urban and rural crashes and develop two independent models.

Table 4.2 Injury Severity in terms of Area Category for Vehicle-Pedestrian/Bicycle Crash

	Urban		Rural	
Severity Level	**Frequency**	**Percent (%)**	**Frequency**	**Percent(%)**
0 - Property Damage Only	94	10.4	10	8.62
1 - Complaint of Pain	450	49.8	32	27.59
2 - Moderate Injury	272	30.1	47	40.52
3 - Incapacitated	74	8.2	17	14.66
4 - Killed	12	1.3	10	8.62
	902	100	116	100

The crash database used to develop injury severity model for vehicle-vehicle crash include crash data from police-reported motor vehicle crashes occurring in New Jersey in of 2000. An one-year period of crash data was sufficient for the development of the vehicle-vehicle crash model because there were many vehicle-vehicle crashes on the roadways compared to the number of vehicle-pedestrian/bicyclist crashes. Detailed information about all reported traffic crashes was also obtained from the New Jersey

Department of Transportation (NJDOT) accident database, the NJDOT straightline diagrams and field collected data. Only crash data from selected roadways in various counties in New Jersey were used for statistical analysis due to the large number of crashes. These roadways include eight urban roadways and seven rural roadways. The roadways used to develop the injury severity model include Rt.5, Rt.7, CR501, CR551, CR585, CR612 and CR667 in Burlington county, and Broad Street in the city of Newark. The data set contains 3414 urban and 2263 rural motor vehicle crashes. Table 4.3 present variables used in developing the injury severity model for vehicle-vehicle crashes. The injury severity data is also summarized by injury severity level in Table 4.4.

It can be seen from Table 4.3 that the majority of the vehicle-vehicle crashes, both in urban and rural areas, occurred on straight highways (91.6% in urban and 94.9% in rural), on roadways with dry surface conditions (75.9% in urban and 78.6% in rural), during clear weather conditions (80.4% in urban and 81.9% in rural), and during day light conditions (72.6% in urban and 71.1% in rural). Table 4.3 also shows that the average posted speed limit is about 25 mph for urban roadways and about 40 mph for rural roadways. The annual average daily traffic (AADT) per lane is 5697 and 4658 in urban and rural roadways respectively. Similar to the vehicle-pedestrian/bicycle model, the average shoulder width in rural roadways is larger than that in urban roadways, while the average pavement width is smaller in rural roadways. In addition, Table 4.4 shows most of the studied vehicle-vehicle crashes only caused property damage (83.1% in urban and 82.8% in rural). Crashes resulting in serious injury or death of the vehicle occupants represented only a very small proportion of all crashes(0.3% in urban and 1.2% in rural).

Table 4.3 Model Variables Identification for Vehicle-Vehicle Crash

Variable	Description	Mean	
		Urban	Rural
Y	Injury Severity as dependent variable with 5 levels		
Continuous Variables			
SL	Posted Speed Limit (mph)	27.17	39.98
PV	Pavement Width (ft)	55.83	48.56
NOL	Number of Lanes	3.617	3.37
AADTPL	Average Annual Daily Traffic per Lane (vpdpl), divided by 1000	5.697	4.258
SH	Shoulder Width (ft)	0.529	7.64
MW	Median Width (ft)	0.088	
Categorical Variables			
UMA	=1 if road is urban minor arterial; =0 otherwise	0.282	
UC	=1 if road is urban collector; =0 otherwise	0.064	
UL	=1 if road is urban local; =0 otherwise	0.066	
RMA	=1 if road is rural minor arterial; =0 otherwise		0.0627
RMAC	=1 if road is rural major collector; =0 otherwise		0.392
RMIC	=1 if road is rural minor collector; =0 otherwise		0.0393
RCSTRI	=1 if road is straight; =0 otherwise	0.916	0.949
SCDRY	=1 if road is dry; =0 otherwise	0.759	0.786
WTCLEAR	=1 if weather is clear; =0 otherwise	0.804	0.819
LCDAY	=1 if day light condition; =0 otherwise	0.726	0.711

Table 4.4 Injury Severity in Terms of Victims Category

	Urban		Rural	
Severity Level	**Frequency**	**Percentage(%)**	**Frequency**	**Percentage(%)**
0 - Property Damage Only	2838	83.1%	1876	82.8%
1 - Complaint of Pain	495	14.4%	275	12.1%
2 - Moderate Injury	70	2%	82	3.6%
3 - Incapacitated	7	0.2%	21	0.9%
4 - Killed	4	0.1%	9	0.3%
	3414	100%	2263	100%

4.2.2 Injury Severity Model Results

Using the crash data from the NJDOT database, injury severity models, including models for urban vehicle-vehicle crashes, urban vehicle-pedestrian/bicyclist crashes, rural vehicle-vehicle crashes, and rural vehicle-pedestrian/bicyclist crashes, were developed in this study. The coefficient estimates and p-values for each independent variable for the urban vehicle-vehicle and urban vehicle-pedestrian/bicyclist crash injury severity model are shown in Table 4.5. For the urban injury severity model for vehicle-pedestrian/bicyclist crashes, where a 90% confidence level was used to identify significant variables, the variables identified as significant in determining the severity of pedestrian/bicyclist include: posted speed limit, AADT per lane, road type, surface condition, light condition, median type, age of victim. Similarly, under a 90% confidence interval, the variables identified as significant in determining the severity of vehicle occupants include: posted speed limit, number of lanes, road type, road curvature, weather condition, and light condition. It can be concluded from the model results that the posted speed limit, road classification, and light condition have a significant impact on injury severity both for vehicle-pedestrian/bicycle crashes and vehicle-vehicle crashes. There are additional independent variables that impact injury severity in only one of the two models. For example, weather condition only has an impact on injury severity caused by vehicle-vehicle crashes while the surface condition only influences injury severity in vehicle-pedestrian/bicycle crashes.

Table 4.5 Injury Severity Models for Urban Area with All Variables

Parameter	Vehicle-Ped./Bic.		Vehicle-Vehicle	
	Estimation	P-Value	Estimation	P-Value
Constant	-0.2507	0.5206	-1.3667	0.0001
Speed Limit	0.0214	0.0018	0.03797	0.0000
Pavement Width	0.0038	0.3712	0.0056	0.1658
Number of lanes	0.00565	0.9069	-0.1565	0.0180
AADTPL	0.0216	0.0755	0.02159	0.2016
Shoulder Width	0.00297	0.6343	-0.0035	0.8349
Median Width	0.01162	0.2994	-0.0278	0.6042
Urban Minor Arterial	0.3116	0.007	-0.0451	0.6558
Urban Collector	-0.0167	0.9544	-0.4665	0.0020
Urban Local	0.1279	0.7083	0.244	0.0592
RSSATE	0.0993	0.3320		
RCSTRIG	-0.026	0.8988	-0.2017	0.0236
SCDRY	0.3036	0.1121	-0.0284	0.8127
WTCLEAR	-0.2609	0.1889	-0.2508	0.0469
LCDAY	-0.2814	0.0005	-0.1729	0.0017
RDBNOMED	0.2876	0.0174		
AGE65	0.3362	0.0088		
MALE	0.09685	0.2273		
VTCAR	0.07568	0.3717		
PED	0.2738	0.0040		
μ_1	1.57	0.0000	1.05	0.0000
μ_2	2.67	0.0000	1.83	0.0000
μ_3	3.65	0.0000	2.18	0.0000
Log Likelihood	-1055.850		-1775.665	
Restricted Log Likelihood	-1088.433		-1822.731	
Chi-Squared	65.17		94.13	
Degree of Freedom	19		13	
Significance Level	0.0000000		0.0000000	

As stated in chapter 3, ordered probit models were also developed using significant variables only. The final model estimations and p-values are shown in Table 4.6. Model 1 represents the injury severity model for vehicle-pedestrian/bicycle crashes in urban areas and Model 2 represents the injury severity model for vehicle-vehicle crashes in urban areas. The final models indicate that all the variables found to be significant when all variables are used to develop the models remain significant in the final models.

Table 4.6 Injury Severity Models for Urban Area with Significant Variables

Parameter	Vehicle-Ped./Bic. (**Model 1**)		Vehicle-Vehicle (**Model 2**)	
	Estimation	P-Value	Estimation	P-Value
Constant	0.1158	0.6433	-0.8617	0.0017
Speed Limit	0.0243	0.0000	0.0272	0.0000
Number of lanes			-0.0969	0.0024
AADTPL	0.0242	0.0338		
Urban Minor Arterial	0.2198	0.0341		
Urban Collector			-0.4173	0.0002
Urban Local			0.2568	0.0368
RCSTRIG			-0.2042	0.0200
SCDRY				
WTCLEAR			-0.2216	0.0002
LCDAY	-0.264	0.0007	-0.184	0.0007
RDBNOMED	0.2099	0.0435		
AGE65	0.3389	0.0071		
PED	0.2314	0.0073		
μ_1	1.56	0.0000	1.06	0.0000
μ_2	2.65	0.0000	1.83	0.0000
μ_3	3.63	0.0000	2.18	0.0000
Log Likelihood	-1061.565		-1779.905	
Restricted Log Likelihood	-1088.433		-1822.731	
Chi-Squared	53.74		85.65	
Degree of Freedom	8		7	
Significance Level	0.0000000		0.0000000	

It can be seen from Table 4.6 that an increase in posted speed limit (β=0.0243) or in AADT per lane (β=0.0242) will result in more serious injury severity sustained by pedestrian or bicyclist involved in vehicle-pedestrian/bicycle crash on urban roadways. Similar impacts of categorical independent variables on the injury severity for pedestrians or bicyclists can also be seen. A roadway without median (β=0.2099) results in a higher probability of severe injury severity than a roadway with a median. A crash occurs during day light conditions (β=-0.264) decreases the probability of severe injury severity. A crash on an urban minor arterial (β=0.2198) has a lower probability of severe injury when compared to the probability of a severe injury on an urban principal arterial.

Table 4.6 also shows that the injury severity level sustained by vehicle occupants in vehicle-vehicle crashes tends to be more serious under higher posted speed limit (β=0.0272), while an increase in the number of lanes (β=-0.0969) result in less serious injury severity for vehicle occupants. In addition, clear weather condition (β=-0.2216), day light condition (β=-0.184) decrease injury severity. Compared to a curve roadway, a straight roadway (β=-0.2042) can reduce the injury severity of vehicle occupants. A crash on an urban collector (β=-0.4173) has a lower probability of severe injury when compared to probability of severe injury on an urban principal arterial. The probability of a severe injury on an urban local roadway (β=0.2568) is greater than the probability of a severe injury on an urban principal arterial.

Tables 4.7 and 4.8 indicate the marginal effects of significant independent variables on the probabilities of each injury severity level. The tables contain the increased or decreased probabilities in each injury severity level with the change of significant independent variables. For example, when other variables are kept constant in a vehicle-pedestrian/bicycle crash, a 10 mph increase in posted speed limit on urban roadways will decrease the probability of PDO (property damage only) by 4.2%, and minor injury by 5.2%, whereas it will increase the injury severity of moderate injury by 5.5%, incapacitated by 3.2%, and killed by 0.7%. In a vehicle-vehicle crash, however, increasing the posted speed limit by 10 mph will reduce the probability of PDO by 6.7% while increasing the severity level of minor injury by 5.3%, moderate injury by 1.2%, incapacitated by 0.1%, and killed by 0.1%. Therefore, it can be concluded that the posted speed limit has a much greater impact on the probability of severe injury for pedestrian or bicycle in vehicle-pedestrian crashes than it has for vehicle occupants in vehicle-vehicle crashes. As for road classification as a categorical variable, compared to a vehicle-pedestrian/bicycle crash on an urban principal arterial, a vehicle-vehicle crash on an urban minor arterial reduces the probability of a property damage crash by 3.78%, and minor injury by 4.69% while increasing the probability of moderate injury by 4.95%, incapacitated by 2.93%, and killed by 0.59% when all other independent variables remain the same.

Table 4.7 Marginal Effects of Significant Variables in Urban Model for Vehicle-Pedestrian/Bicycle Crash

Variable	Marginal Effects				
	Y=0	Y=1	Y=2	Y=3	Y=4
Constant	-0.0199	-0.0247	0.0261	0.0155	0.003
SL	-0.0042	-0.0052	0.0055	0.0032	0.0007
AADTPL	-0.0042	-0.0052	0.0055	0.0032	0.0007
UMA	-0.0378	-0.0469	0.0495	0.0293	0.0059
LCDAY	0.0454	0.0563	-0.0594	-0.0352	-0.0071
RDBNOMED	-0.0361	-0.0448	0.0473	0.028	0.0056
AGE65	-0.0583	-0.0723	0.0763	0.0452	0.0091
PED	-0.0398	-0.0494	0.0521	0.0309	0.0062

Table 4.8 Marginal Effects of Significant Variables in Urban Model for Vehicle-Vehicle Crash

Variable	Marginal Effects				
	Y=0	Y=1	Y=2	Y=3	Y=4
Constant	0.2124	-0.1692	-0.0366	-0.0043	-0.0023
SL	-0.0067	0.0053	0.0012	0.0001	0.0001
NOL	0.0239	-0.019	-0.0041	-0.0005	-0.0003
UC	0.1029	-0.0819	-0.0177	-0.0021	-0.0012
UL	-0.0633	0.0504	0.0109	0.0013	0.0007
RCSTRIGHT	0.0503	-0.0401	-0.0087	-0.001	-0.0005
WTCLEAR	0.0546	-0.0435	-0.0094	-0.0011	-0.0006
LCDAY	0.0454	-0.0361	-0.0078	-0.0009	-0.0006

The probability of each injury severity level sustained by a pedestrian or bicyclist in urban roadways can be expressed as follows:

$$P(Y=0)=\phi(0-\beta' X) \tag{4.1}$$
$$=\phi(0-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$

$$P(Y=1)=\phi(\mu_1-\beta' X)-\phi(0-\beta' X) \tag{4.2}$$
$$=\phi(1.56-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$
$$-\phi(0-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$

$$P(Y=2)=\phi(\mu_2-\beta' X)-\phi(\mu_1-\beta' X) \tag{4.3}$$
$$=\phi(2.65-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$
$$-\phi(1.56-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$

$$P(Y=3)=\phi(\mu_3-\beta' X)-\phi(\mu_2-\beta' X) \tag{4.4}$$
$$=\phi(3.63-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$
$$-\phi(2.65-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$

$$P(Y=4)=1-\phi(\mu_3-\beta' X) \tag{4.5}$$
$$=1-\phi(3.63-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED)$$

Likewise, the probabilities of each injury severity level in the urban model for vehicle-vehicle crashes are given by the following equations:

$$P(Y=0)=\phi(0-\beta' X) \tag{4.6}$$
$$=\phi(0-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY)$$

$$P(Y=1)=\phi(\mu_1-\beta' X)-\phi(0-\beta' X)$$
$$=\phi(1.06-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY) \tag{4.7}$$
$$-\phi(0-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY)$$

$$P(Y=2)=\phi(\mu_2-\beta' X)-\phi(\mu_1-\beta' X)$$
$$=\phi(1.83-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY) \tag{4.8}$$
$$-\phi(1.06-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY)$$

$$P(Y=3)=\phi(\mu_3-\beta' X)-\phi(\mu_2-\beta' X)$$
$$=\phi(2.18-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY) \quad (4.9)$$
$$-\phi(1.83-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY)$$

$$P(Y=4)=1-\phi(\mu_3-\beta' X)$$
$$=1-\phi(2.18-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY) \quad (4.10)$$

Table 4.9 provides the coefficients and p-values for each of the independent variables. For rural locations and for both vehicle-pedestrian/bicycle and vehicle-vehicle crashes, it can be seen from the table that variables significantly impacting injury severity of pedestrian and bicyclist include speed limit, pavement width, and type of victim (pedestrian or bicyclist). In addition, light condition is regarded as significant since the p-value is close to 0.1. Under a 90% confidence interval, the variables identified as significant in determining the severity of vehicle occupants include: posted speed limit, pavement width, AADT per lane, shoulder width, road type, and weather condition. The final model estimations and p-values are shown in Table 4.10. The final ordered probit model coefficient estimates are obtained using only significant variables. Model 3 represents the ordered probit model for vehicle-pedestrian/bicycle crashes and Model 4 for vehicle-vehicle crashes in a rural area.

Table 4.9 Injury Severity Models for Rural Area with All Variables

Parameter	Vehicle-Ped./Bic.		Vehicle-Vehicle	
	Estimation	P-Value	Estimation	P-Value
Constant	0.2317	0.8790	-1.8885	0.0000
Speed Limit	0.077	0.0138	0.03424	0.0000
Pavement Width	-0.022	0.0811	-0.01195	0.0123
Number of lanes	-0.0123	0.9408	0.05157	0.3859
AADTPL	-0.00505	0.9596	-0.04775	0.0166
Shoulder Width	-0.03717	0.3219	-0.02389	0.0003
Median Width	-0.0042	0.9053		
Rural Minor Arterial	-0.4945	0.4066	0.4118	0.0401
Rural Major Collector	0.3861	0.5683	-0.08669	0.6236
Rural Minor Collector	-0.8688	0.5935	-0.149	0.4475
RSSATE	0.2518	0.4833		
RCSTRIG	0.6791	0.2007	-0.09734	0.5556
SCDRY	0.2227	0.8589	-0.1827	0.1965
WTCLEAR	-0.748	0.5829	0.4417	0.0052
LCDAY	-0.3676	0.1320	0.0162	0.8246
RDBNOMED	-0.4155	0.4670		
AGE65	0.323	0.4551		
PED	0.5564	0.0143		
μ_1	1.15	0.0000	0.74	0.0000
μ_2	2.46	0.0000	1.34	0.0000
μ_3	3.33	0.0000	1.79	0.0000
Log Likelihood	-145.2676		-1292.309	
Restricted Log Likelihood	-165.3396		-1351.531	
Chi-Squared	40.14		118.05	
Degree of Freedom	17		11	
Significance Level	0.0012		0.0000000	

Table 4.10 indicates that a higher posted speed limit (β =0.0374) will increase the probability of a severe injury sustained by a pedestrian or a bicyclist in a vehicle-pedestrian/bicycle crash on rural roadway. Wider pavements (β =-0.0125), on the other hand, reduce the probability of a severe injury when all other variables are kept the same. For the impact of categorical independent variables on injury severity for pedestrians or bicyclists, day light condition (β =-0.3223) decreases injury severity, and compared to a

bicyclist, a pedestrian (β=0.5121) has a greater probability of severe injury when other independent variables remain the same.

For vehicle-vehicle crashes on rural roadways, Table 4.10 indicates that vehicle occupants will suffer more serious injury with an increase in posted speed limit (β=0.0366), while roadways with greater pavement width (β=-0.0103), or higher AADT per lane (β=-0.0329), or greater shoulder width (β=-0.0258) result in lower probability of severe injury for vehicle occupants when other variables are kept the same. In addition, clear weather condition (β=0.2803) also increases injury severity in rural roadways when other variables are held constant. The difference in the impact of clear weather condition on injury severities of vehicle occupants for urban and rural models may be due to the fact that drivers tend to travel at higher speeds on rural roadways during clear weather conditions, while on urban roadways they do not increase vehicle speed due to greater traffic volumes. Moreover, a crash on a rural minor arterial (β=0.4534) has a higher probability of a more severe injury for vehicle occupants when compared to the probability of severe injury on a rural principal arterial.

Table 4.10 Injury Severity Models for Rural Area with Significant Variables

Parameter	Vehicle-Ped./Bic. **(Model 3)**		Vehicle-Vehicle **(Model 4)**	
	Estimation	P-Value	Estimation	P-Value
Constant	0.3446	0.4998	-1.8849	0.0000
Speed Limit	0.0421	0.0000	0.0366	0.0000
Pavement Width	-0.0117	0.0722	-0.0103	0.0000
AADTPL			-0.0329	0.0440
Shoulder Width			-0.0258	0.0000
Rural Minor Arterial			0.4534	0.0008
WTCLEAR			0.2803	0.0024
PED	0.5426	0.0094		
μ_1	1.10	0.0000	0.74	0.0000
μ_2	2.33	0.0000	1.33	0.0000
μ_3	3.13	0.0000	1.79	0.0000
Log Likelihood	-151.3768		-1295.459	
Restricted Log Likelihood	-165.3396		-1351.531	
Chi-Squared	27.93		112.14	
Degree of Freedom	3		6	
Significance Level	0.000004		0.000000	

Tables 4.11 and 4.12 show the marginal effects of significant variables on injury severity. The results indicate that increasing the posted speed limit results in higher severity levels in rural areas when compared to the injury severity in urban areas. For example, a 10 mph increase of the posted speed limit on rural roadways for Model 3, which is the injury severity model for vehicle-pedestrian/bicycle crashes on rural roadways, increases the probability of a fatal crash involving pedestrian or bicyclist by 4.6%, and the probability of incapacitated injury by 7.5% when other independent variables are held constant. While for a pedestrian or bicyclist on urban roadways for Model 1, which is the injury severity model for vehicle-pedestrian/bicycle crashes on urban roadways, the probability of a fatal crash and the probability of incapacitated injury increase by 0.7% and 3.2% respectively with a 10 mph increase in posted speed limit.

Table 4.11 Marginal Effects of Significant Variables in Rural Area for Vehicle-Pedestrian/Bicyclist Crash

Variable	Marginal Effects				
	Y=0	Y=1	Y=2	Y=3	Y=4
Constant	-0.0433	-0.0824	0.0207	0.0612	0.0438
SL	-0.0053	-0.0101	0.0033	0.0075	0.0046
PV	0.0015	0.0028	-0.0009	-0.0021	-0.0013
PED	-0.0682	-0.1298	0.0420	0.0964	0.0596

Table 4.12 Marginal Effects of Significant Variables in Rural Area for Vehicle-Vehicle Crash

Variable	Marginal Effects				
	Y=0	Y=1	Y=2	Y=3	Y=4
Constant	0.4561	-0.2895	-0.1172	-0.0339	-0.0155
SL	-0.0089	0.0056	0.0023	0.0007	0.0003
PV	0.0025	-0.0016	-0.0006	-0.0002	-0.0001
AADTPL	0.008	-0.0051	-0.002	-0.0006	-0.0003
SH	0.0062	-0.004	-0.0016	-0.0005	-0.00001
RMA	-0.1097	0.0696	0.0282	0.0082	0.0037
WTCLEAR	-0.0678	0.043	0.0174	0.005	0.0024

The probabilities of injury severity level sustained by a pedestrian or bicyclist in rural areas are stated as,

$$P(Y=0)=\phi(0-\beta' X)=\phi(0-(0.042SL-0.012PV+0.54PED)) \tag{4.11}$$

$$\begin{aligned}P(Y=1)&=\phi(\mu_1-\beta' X)-\phi(0-\beta' X)\\&=\phi(1.10-(0.042SL-0.012PV+0.54PED)-\phi(0-(0.042SL-0.012PV+0.54PED))\end{aligned} \tag{4.12}$$

$$\begin{aligned}P(Y=2)&=\phi(\mu_2-\beta' X)-\phi(\mu_1-\beta' X)\\&=\phi(2.33-(0.042SL-0.012PV+0.54PED)-\phi(1.10-(0.042SL-0.012PV+0.54PED))\end{aligned} \tag{4.13}$$

$$\begin{aligned}P(Y=3)&=\phi(\mu_3-\beta' X)-\phi(\mu_2-\beta' X)\\&=\phi(3.13-(0.042SL-0.012PV+0.54PED)-\phi(2.33-(0.042SL-0.012PV+0.54PED))\end{aligned} \tag{4.14}$$

$$P(Y=4)=1-\phi(\mu_3-\beta' X)=1-\phi(3.13-(0.042SL-0.012PV+0.54PED)) \tag{4.15}$$

Similarly, the probabilities of each injury severity level for vehicle occupants in rural roadways are given by the following equations:

$$P(Y=0)=\phi(0-\beta' X)$$
$$=\phi(0-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR)) \quad (4.16)$$

$$P(Y=1)=\phi(\mu_1-\beta' X)-\phi(0-\beta' X)$$
$$=\phi(0.74-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR)) \quad (4.17)$$
$$-\phi(0-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR))$$

$$P(Y=2)=\phi(\mu_2-\beta' X)-\phi(\mu_1-\beta' X)$$
$$=\phi(1.33-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR)) \quad (4.18)$$
$$-\phi(0.74-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR))$$

$$P(Y=3)=\phi(\mu_3-\beta' X)-\phi(\mu_2-\beta' X)$$
$$=\phi(1.79-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR)) \quad (4.19)$$
$$-\phi(1.33-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR))$$

$$P(Y=4)=1-\phi(\mu_3-\beta' X)$$
$$=1-\phi(1.79-(-1.89+0.037SL-0.01PV-0.033AADTPL-0.026SH+0.45RMA+0.28WTCLEAR)) \quad (4.20)$$

4.2.3 Injury Severity Model Test

Four final ordered probit models were developed in this research. The models include an injury severity model for vehicle-pedestrian/bicycle crashes in urban areas (Model 1), an injury severity model for vehicle-vehicle crashes in urban areas (Model 2), an injury severity model for vehicle-pedestrian/bicycle crashes in rural areas (Model 3), and an injury severity model for vehicle-vehicle crashes in rural areas (Model 4). The following contains the goodness-of-fit tests performed for these models using a likelihood ratio test as presented in chapter 3.

For Model 1, the likelihood ratio test compares at first the log likelihood of the model that contains significant variables only to the log likelihood of the model that contains all independent variables as follows,

$$G=-2[\ln(L')-\ln(L)]=-2[-1061.565-(-1055.850)]=11.43$$

The degrees of freedom, which is defined as the difference between the number of parameter in these two models, is 11. The chi-square value associated with the degrees of freedom is shown below based on a 90% confidence level:

$$\chi^2(11,0.1) = 17.275$$

The null hypotheses, $H_0 : \beta_k = 0$, is accepted since G=11.43< $\chi^2(11,0.1) = 17.275$. This result indicates that the coefficients of all insignificant variables are equal to zero. Therefore, it is reasonable to keep only the significant variables in Model 1.

Upon the completion of the last step, it is necessary to test the significance of the whole model. Then we have,

$$G' = -2[\ln(L(0)) - \ln(L(\beta))] = -2[-1088.433 - (-1061.565)] = 53.74$$

Since the degrees of freedom in Model 1 is eight, and $P[\chi^2(8) > 53.74] = 0.000000$ is smaller than 0.1, Model 1 is regarded as statistically significant for a 90% confidence level.

Similarly, the other three models can be tested using the same method. Table 4.13 presents the test results for all the final models. It can be concluded that all ordered probit models in this research are statistically significant.

Table 4.13 Results of Injury Severity Models Significant Test

	Model 1	Model 2	Model 3	Model 4
G	11.43	8.48	12.22	6.3
χ^2	17.275	10.645	21.064	9.236
Accept H_0 ?	Yes	Yes	Yes	Yes
$G^{'}$	53.74	94.13	27.93	112.14
P-value	<0.0000	<0.0000	<0.0000	<0.0000
Is the model significant?	Yes	Yes	Yes	Yes

4.3 Crash Frequency Prediction Model

After the probabilities of the injury level are determined using the injury severity model, crash frequencies were identified to obtain crash cost. Similar to the injury severity models, crash frequency prediction models developed in this research also included both urban and rural models for crashes involving vehicles only, and crashes involving vehicles and pedestrians or bicyclists. However, crashes involving vehicles and pedestrians or bicyclists in rural areas occurred rarely, resulting in difficulties to develop crash frequency models for these rare crashes. Therefore, the average number of crashes during the period of 1997-2000 on selected rural roadways was used to calculate the crash cost for rural roadways.

4.3.1 Data Collection and Analysis

The subset crash data used to develop the vehicle-pedestrian/bicycle crash frequency model for an urban area included nineteen roadways with 359 crashes on 384 roadway segments. The roadway segments varied in length from 0.03 to 1 mile. The roadways where crash data were obtained include CR501 in Hudson County, CR510 in Essex

County, Rt.1 in Hudson, Middlesex, and Mercer Counties, CR603 in Essex County, Rt.27 in Middlesex and Union County, CR508 in Essex County, CR601 in Passaic County, CR506S in Essex County, Rt.28 in Somerset, Middlesex, and Union Counties, Rt.35 in Ocean, Monmouth and Middlesex County, Rt.72 in Ocean County, Rt.21 in Essex County, CR509 in Essex and Union County, CR551 in Camden and Gloucester County, CR514 in Middlesex and Union County, CR537 in Camden County, CR585 in Atlantic County, CR505 in Hudson County, and CR612 in Burlington County. Categorical independent variables such as road character, surface condition, weather condition, and light condition are not included in this model because the crash prediction model of this section predicts the number of crashes in various segments of a roadway, and each crash in a segment occurred under a different situation. In addition, urban local streets are excluded from this model since the detailed straightline diagram for local streets with such kind of crashes is not available. The variables used to develop the crash prediction model for vehicle-pedestrian/bicycle crashes are shown in Table 4.14. The table shows that the average posted speed limit is 36 mph for selected urban roadways, the average shoulder width is 4.7 ft, the average pavement width 44 ft, the average median width 1.17 ft, and the average number of lanes is 3.

Table 4.14 Model Variables for Vehicle-Pedestrian/Bicycle Crash in Urban Area

Variable	Description	Mean
N_Crash	Crash Number	
Continue Variables		
SL	Posted Speed Limit (mph)	36.47
PV	Pavement Width (ft)	44.32
NOL	Number of Lanes	3.05
MW	Median Width (ft)	1.17
SH	Shoulder Width (ft)	4.7
EXPO	Exposure	3.35
Categorical Variables (Referred Categories are not shown)		
UMA	=1 if road is urban minor arterial; =0 otherwise	0.29
UC	=1 if road is urban collector; =0 otherwise	0.078

Crash data for vehicle-vehicle crashes using the urban and rural model are obtained from crashes in fourteen urban roadways and ten rural roadways in New Jersey during the 1997 to 2000 period. The urban crash data are obtained from 2332 urban segments in Rt.1, Rt.5, Rt.7, Rt.27, Rt.41, Rt.47, Rt.48, Rt.71, Rt.88, Rt.91, Rt.156, Rt.173, Rt.175, and Rt.181. Each segment has a length of 0.2 mile. Also, the roadways used in the rural model for vehicle-vehicle crash frequency include Rt. 30, Rt.31, Rt.45, Rt.48, Rt.50, Rt.94, Rt.173, Rt.181, Rt.202, and Rt. 322. The roadways are divided into 2922 segments with a length of 0.2 mile each, and there are 3643 vehicle crashes on these segments during the 1997 to 2000 period. A series of independent variables, including speed limit, pavement width, number of lanes, AADT, shoulder width, road type, median type, number of intersections in the segments and number of signalized intersections in the segments, are used for the model development. It can be seen from Table 4.15 that the average posted speed limit is about 45 mph for urban roadways and 50 mph for rural roadways. The annual average daily traffic (AADT) is 31,526 and 11,615 for urban and rural roadways respectively. It can also be seen from Table 4.15 that the average shoulder width in rural roadways is larger than that on urban roadways, while the average pavement width and the average number of lanes are smaller in rural roadways. In addition, the average number of intersections and signalized intersections are greater on urban rural roadways.

Table 4.15 Model Variables Identification for Vehicle-Vehicle Crash

Variable	Description	Mean	
		Urban	Rural
	Crash number		
Continue Variables			
N_INTER	Number of intersections in the segment	1.708	0.56
N_SIGINT	Number of signalized intersection in the segment	0.458	0.067
SL	Posted Speed Limit (mph)	42.97	48.47
PV	Pavement Width (ft)	43.81	33.54
NOL	Number of Lanes	3.4	2.71
AADT	Average Annual Daily Traffic	31526	11615
SH	Shoulder Width (ft)	9.38	13.53
Categorical Variables (Referred Categories are not shown)			
UMA	=1 if road is urban minor aRt.erial; =0 otherwise	0.3962	
UC	=1 if road is urban collector; =0 otherwise	0.012	
UL	=1 if road is urban local; =0 otherwise	0.012	
RMA	=1 if road is rural minor aRt.erial; =0 otherwise		0.5742
RMAC	=1 if road is rural major collector; =0 otherwise		0.05065
RMIC	=1 if road is rural minor collector; =0 otherwise		0.04107
MEDBARRI	=1 if road median is barrier; =0 otherwise	0.4253	0.0438
MEDGM	=1 if road median is grass; =0 otherwise	0.0029	0.1164

4.3.2 Crash Frequency Model Results

The coefficient estimation and P-values of the crash frequency prediction model for vehicle-pedestrian or bicyclist crash in urban areas are shown in Table 4.16. Posted speed limit, road type, and vehicle exposure are identified as significant variables. Vehicle exposure is the number of vehicle kilometers traveled per year as shown in equation (4.21). A final model (Model 5) is developed using significant variables only as shown in Table 4.17. The results indicate that higher posted speed limits (β=-0.089) on urban roadways are likely to decrease crash frequency between a vehicle and a pedestrian or bicyclist. The possible reasons are the roadways with higher speed limits generally have less pedestrian or bicyclist volume, and geometric design standards on those roadways are much higher, such as wider pavement and an increased number of lanes. The table also shows that there are fewer crashes on an urban minor arterial (β=-0.8147) compared to an urban principal arterial. The possible reason is that there is less vehicle volume on an urban minor arterial than on an urban principal arterial.

Table 4.16 Crash Frequency Model for Vehicle-Pedestrian/Bicycle in Urban Area with All Variables

Parameter	**Estimation**	**P-Value**
Constant	2.3784	0.0095
Speed Limit	-0.0689	0.0024
Pavement Width	0.00726	0.619
Number of lanes	-0.1569	0.337
Shoulder Width	-0.028	0.2246
Median Width	0.0149	0.5829
Urban Minor Arterial	-0.9079	0.0022
Urban Collector	-0.8547	0.1689
Exposure	0.1112	0.0067
Alpha	2.6042	0.0000
Log Likelihood	-448.4549	
Restricted Log Likelihood	-591.4299	
R^2	0.24	
Significance Level	0.0000000	

Table 4.17 Crash Frequency Model for Vehicle-Ped./Bic. in Urban Area with Significant Variables

Parameter (Model 5)	**Estimation**	**P-Value**
Constant	2.7497	0.0000
Posted Speed Limit	-0.089	0.0000
Urban Minor Arterial	-0.8147	0.0012
Exposure	0.12	0.0016
Alpha	2.7317	0.0000
Log Likelihood	-451.3627	
Restricted Log Likelihood	-605.9680	
R^2	0.25	
Significance Level	0.0000000	

The urban crash frequency model for vehicle-pedestrian/bicycle crashes is as stated in equation (4.21). Vehicle exposure is considered as an independent variable in this model based on conclusions by previous research (Miaou,1994), which showed that exposure had a positive impact on crash frequency.

$$N\_Crash = Exp(2.75 - 0.089SL - 0.815UMA + 0.12EXPOSURE) \qquad (4.21)$$

Where

$$EXPOSURE = \frac{AADT * Seglength * 365}{10^6}$$

N_Crash: Number of crashes on a segment

$Exposure$ Vehicle exposure value

SL: Posted speed limit

$Seglength$: Length of a segment

$AADT$: Annual Average Daily Traffic

UMA: Urban Minor Arterial

Table 4.18 presents the coefficient estimation and P-values of the independent variables for vehicle-vehicle crashes in urban areas. There are more independent variables in the vehicle-vehicle model than in the vehicle-pedestrian/bicycle model because of added variables such as the number of intersections and number of signalized intersections. These variables are included because they are available for vehicle-vehicle crashes through the NJDOT straightline diagram. Variables found to significantly impact vehicle-vehicle crash frequency in urban areas include the number of intersections, speed limit, AADT, pavement width, number of lanes, median type, and road type. The significant variables are also used to develop the final crash frequency model (Model 6) for vehicle-vehicle crashes in urban areas. The coefficient estimations and p-values of the independent variables are shown in Table 4.19. It can be seen from the table that independent variables such as the number of intersections (β =0.1318), number of signalized intersections (β =0.7082), AADT (β =0.000014), and number of lanes

(β=0.1896) have positive impacts on vehicle-vehicle crash frequency in urban areas, while posted speed limit (β=-0.0262), pavement width (β=-0.0069), and grass median (β=-0.378) negatively impact crash frequency. Compared to an urban principal arterial, a roadway with other classifications such as an urban minor arterial, an urban collector, and an urban local street, can reduce the vehicle-vehicle crash frequency. This can be explained by the fact that roadways with more intersections, or greater AADT, or more lanes are locations where it is more likely to have a crash between vehicles because of the greater vehicle exposure, while a wider pavement and grass median provide drivers with better driving conditions, resulting in fewer crashes. The reason why the speed limit has a negative impact on crash frequency may also be attributed to the fact that roadways with higher speed limits are of much higher geometric standards when compared to roadways with lower speed limits. Moreover, studies conducted by Solomon (1964) and Cirillo (1968) pointed out the strong relationship between speed deviation and vehicle crash involvement. As presented in Chapter 2, the U-shape curve showed that a vehicle was more likely to be involved in a crash when there was a greater deviation between a vehicle's speed and the average speed of vehicles. Therefore, it is possible that the reason for the negative impact of speed limit on crash frequency is that the speed deviation on roadways with higher speed limits is smaller due to good driving conditions, thus reducing the crash frequency on those roadways. In addition, compared to an urban principal roadway, other roadway classifications such as urban minor arterial, urban collector, and urban local have much less traffic volume (AADT), thus resulting in fewer crashes.

Table 4.18 Crash Frequency Model for Vehicle-Vehicle Crashes in Urban Area with All Variables

Parameter	Estimation	P-Value
Constant	1.9143	0.0000
N_INTER	0.1312	0.0000
N_SIGINT	0.6969	0.0000
AADT	0.1515E-04	0.0000
Speed Limit	-0.02657	0.0000
Pavement Width	-0.005616	0.0935
Number of lanes	0.1804	0.0002
Shoulder Width	0.001683	0.5117
MEDBARRI	-0.09832	0.4253
MEDGM	-0.4611	0.0029
Urban Minor ARt.erial	-0.4155	0.0000
Urban Collector	-1.1813	0.0001
Urban Local	-2.4669	0.0000
Alpha	0.7641	0.0000
Log Likelihood	-7015.564	
Restricted Log Likelihood	-11756.51	
R^2	0.403	
Significance Level	0.0000000	

Table 4.19 Crash Frequency Model for Vehicle-Vehicle Crashes in Urban Area with Significant Variables

Parameter (Model 6)	Estimation	P-Value
Constant	1.9515	0.0000
N_INTER	0.1318	0.0000
N_SIGINT	0.7082	0.0000
AADT	0.1365E-04	0.0000
Speed Limit	-0.0262	0.0000
Pavement Width	-0.0069	0.0265
Number of lanes	0.1896	0.0001
MEDGM	-0.378	0.0012
Urban Minor ARt.erial	-0.4184	0.0000
Urban Collector	-1.1861	0.0001
Urban Local	-2.5027	0.0000
Alpha	0.7589	0.0000
Log Likelihood	-7010.864	
Restricted Log Likelihood	-11542.11	
R^2	0.393	
Significance Level	0.0000000	

The Crash frequency between vehicles in urban roadways can be expressed as,

$$N\_Crash = Exp(1.95 + 0.13N\_Inter + 0.71N\_Siginter + 0.000014AADT - 0.026SL \\ -0.0069PV + 0.19NOL - 0.38MedGM - 0.42UMA - 1.19UC - 2.5UL) \quad (4.22)$$

Where

N_Inter : Number of intersections on a segment

$N\_Siginter$: Number of signalized intersections on a segment

PV : Pavement width

NOL : Number of lanes

$MedGM$: Grass median

UL : Urban local street

A negative binomial model was also used to predict crash frequency on rural roadways. Using LIMDEP to analyze the crash data, the variables identified as significant in the rural model as shown in Table 4.20 include tnumber of intersections, number of signalized intersection, speed limit, AADT, median type, and road type. Table 4.21 shows the coefficient estimation and p-values for all significant variables of the final model for vehicle-vehicle crashes in rural areas (Model 7). Similar to the urban model, independent variables such as number of intersections, number of signalized intersections, and posted speed limit also has positive impact on vehicle-vehicle crash frequency in rural areas. Also, compared to a rural principal arterial, a rural minor collector has fewer crashes between vehicles. A grass median has an opposite impact on crash frequency for an urban area than a rural area, this may be attributed to different geometric characteristics and drivers' behaviors.

The predicted number of crashes between vehicles in rural roadways is stated as:

$$N\_Crash = Exp(1.13 + 0.24N\_Inter + 1.04N\_Siginter + 0.000021AADT \\ -0.034SL + 0.52MedB + 0.54MedGM - 0.24RMIC) \tag{4.23}$$

Table 4.20 Crash Frequency Model for Vehicle-Vehicle Crashes in Rural Area with All Variables

Parameter	Estimation	P-Value
Constant	1.4383	0.0000
N_INTER	0.2125	0.0000
N_SIGINT	1.052	0.0000
AADT	0.000019	0.0000
Speed Limit	-0.04749	0.0000
Pavement Width	0.00458	0.5316
Number of lanes	0.08912	0.43
Shoulder Width	-0.00357	0.4339
MEDBARRI	0.4672	0.0024
MEDGM	0.4864	0.0000
Rural Minor Arterial	0.077	0.2956
Rural Major Collector	-0.1514	0.2411
Rural Minor Collector	-0.2657	0.0707
Alpha	0.8512	0.0000
Log Likelihood	-4120.192	
Restricted Log Likelihood	-4583.594	
R^2	0.104	
Significance Level	0.0000000	

Table 4.21 Crash Frequency Model for Vehicle-Vehicle Crashes in Rural Area with Significant Variables

Parameter (Model 7)	Estimation	P-Value
Constant	1.1335	0.0000
N_INTER	0.2448	0.0000
N_SIGINT	1.0433	0.0000
AADT	0.000021	0.0000
Speed Limit	-0.0342	0.0000
MEDB	0.5167	0.0001
MEDGM	0.5433	0.0000
Rural Minor Collector	-0.2362	0.0867
Alpha	0.8632	0.0000
Log Likelihood	-4129.918	
Restricted Log Likelihood	-4610.171	
R^2	0.104	
Significance Level	0.0000000	

4.3.3 Crash Frequency Model Test

Three negative binomial models are developed in this research to predict crash frequencies. These models include a crash frequency model for vehicle-pedestrian/bicycle crashes in urban areas (Model 5), a crash frequency model for vehicle-vehicle crashes in urban areas (Model 6), and a crash frequency model for vehicle-vehicle crashes in rural areas (Model 7). As indicated before, crashes involving vehicles and pedestrians or bicyclists in rural areas occurred rarely, resulting in difficulties to develop crash frequency models for these rare crashes. Therefore, the average number of crashes during the 1997-2000 period on selected rural roadways was used to calculate the crash cost for rural roadways. The values of the overdispersion parameter in the three crash frequency models imply the appropriateness of a negative binomial model rather than a Poisson model. Additionally, it can be seen from the Tables 4.17, 4.19, and 4.21 that the R squares for these three models are 0.25, 0.393, and 0.104, respectively, indicating a acceptable fitting of the data.

CHAPTER 5

CASE STUDY

5.1 Introduction

The models developed in the previous chapter are used to predict the crash frequency and injury severity level when crashes occur. Then the total crash cost on a roadway segment is obtained based on the crash frequency, crash injury severity level, and unit cost of each injury severity level. Since total cost for a roadway segment consists of crash cost, travel time cost, fuel cost, and air emissions cost, CORSIM was used in this research to simulate operational situations on roadways to obtain data of travel time, fuel consumption, and emissions to calculate travel time cost, fuel cost, and air emissions cost, which are the components of total cost. Since a CORSIM simulation should be based on actual geometric information, segments for several roadways in New Jersey were selected to obtain the optimal speed limits based on the methods shown before. Information on AADT on major roadways was provided from the NJDOT database, and signal timings at intersections were collected from the field. However, such information as AADT on minor streets, percentages of turning vehicles, which are necessary for the simulation, was not available in either an existing database or field-collected data. Therefore, assumptions were made about this information. In the simulation, volumes on minor streets and turn vehicle percentages are estimated based on field-collected data, and minor streets between two signalized intersections are combined to one due to the large number of minor streets in theses segments, which causes difficulties in simulation.

One urban roadways and two rural roadways were selected for case studies to identify the optimal speed limit based on total cost. The roadways include Route 1, Route 30, and Route 322. Results of the case studies are shown in the following sections.

5.2 Case Study 1: Route 1 (Milepost: 57.68-58.68)

Route 1 in New Jersey is a roadway extending for 64.88 miles through multiple counties. The roadway has between 3 and 7 lanes, and has posted speed limits ranging from 30 mph to 55 mph. In addition, it has shoulder width varying from 0 to 24 feet, pavement width from 22 to 72 feet, and median width from 0 to 6 feet. The roadway is classified as an urban principal arterial and an urban freeway. In this case study, a 1-mile segment of Rt.1 (MP 57.68 to 58.68) in Hudson County, which is classified an urban principal arterial, is selected for simulation. Detailed geometric and traffic information on this segment is shown in Table 5.1.

Table 5.1 Route 1 Segment Information

Segment	Route 1 (MP 57.68-58.68)
Segment Length	1 mile
Location	North Bergen, Hudson County, NJ
Road Type	Urban Principal Arterial
Posted Speed Limit	40 mph
Pavement Width	40 ft
Shoulder Width	0
Number of Lanes	4
Median Width	0
Median Type	None
AADT	33387
AADTPL (/1000)	8.35
Number of Intersection	17
Number of signalized Intersection	4

5.2.1 Injury Severity Model for Vehicle and Pedestrian/Bicyclist Crash

The injury severity model developed in Chapter 4 is used here to calculate the probabilities of injury severity levels based on specific roadway information. However, data on surface condition, light condition, victim's age and whether he/she is a pedestrian or a bicyclist are unavailable before a crash occurrs, thus assumptions were made that the crash occurred during day light condition between a vehicle and a pedestrian whose age is under 65. Therefore, the injury severity model for Rt. 1 is shown below.

$$
\begin{aligned}
P(Y=0) &= \phi(0-\beta' X) \\
&= \phi(0-(0.024SL+0.024AADTPL+0.22UMA-0.26LCDAY+0.21RDBNO+0.34AGE65+0.23PED) \\
&= \phi(-0.024SL+0.024*8.35-0.22*0+0.26*1-0.21*1+0.34*0-0.23*1) \\
&= \phi(-0.38-0.024SL)
\end{aligned}
\tag{5.1}
$$

$$
\begin{aligned}
P(Y=1) &= \phi(\mu_1-\beta' X)-\phi(0-\beta' X) \\
&= \phi(1.56-0.38-0.024SL)-\phi(-0.38-0.024SL) \\
&= \phi(1.18-0.024SL)-\phi(-0.38-0.024SL)
\end{aligned}
\tag{5.2}
$$

$$P(Y=2) = \phi(\mu_2 - \beta' X) - \phi(\mu_1 - \beta' X) = \phi(2.27 - 0.024SL) - \phi(1.18 - 0.024SL) \quad (5.3)$$

$$P(Y=3) = \phi(\mu_3 - \beta' X) - \phi(\mu_2 - \beta' X) = \phi(3.25 - 0.024SL) - \phi(2.27 - 0.024SL) \quad (5.4)$$

$$P(Y=4) = 1 - \phi(\mu_3 - \beta' X) = 1 - \phi(3.25 - 0.024SL) \quad (5.5)$$

To determine the optimal posted speed limit for a roadway, it is necessary to know the probability of each injury severity under various speed limits. Table 5.2 shows the probability for each injury severity for speed limits from 15 mph to 65 mph. The table shows that higher posted speed limits increase the probabilities of higher injury severity levels. For example, when a pedestrian hit by a vehicle on a roadway with a 25 mph posted speed limit, the probability of incapacitated injury sustained by the pedestrian is 4.35%, while on a roadway with a 65 mph posted speed limit, the probability increases to 19.34%.

Table 5.2 Injury Severities in Different Speed Limits in Vehicle- Pedestrian/Bicycle Crash

SL (mph)	**P (Y=0)**	**P (Y=1)**	**P (Y=2)**	**P (Y=3)**	**P (Y=4)**
15	0.2296	0.5643	0.178	0.0262	0.0019
20	0.1949	0.5631	0.2053	0.0339	0.0028
25	0.1635	0.5555	0.2335	0.0435	0.004
30	0.1357	0.5415	0.2622	0.0549	0.0057
35	0.1112	0.5219	0.2905	0.0684	0.008
40	0.0901	0.497	0.3178	0.0841	0.011
45	0.0721	0.4677	0.3432	0.102	0.015
50	0.0571	0.4349	0.3657	0.1221	0.0202
55	0.0446	0.3997	0.3846	0.1443	0.0268
60	0.0344	0.363	0.3993	0.1682	0.0351
65	0.0262	0.3258	0.4091	0.1934	0.0455

5.2.2 Injury Severity Model for Vehicle-Vehicle Crash

Probabilities of injury severity levels for vehicle-vehicle crashes on Rt. 1 can be obtained from the following equations based on the assumptions that the crashes occurred during clear weather conditions and day light conditions,

$$\begin{aligned} P(Y=0) &= \phi(0-\beta' X) \\ &= \phi(0-(-0.86+0.027SL-0.097NOL-0.42UC+0.26UL-0.2RCSTRI-0.22WTCLEAR-0.18LCDAY) \\ &= \phi(0.86-0.027SL+0.097*4+0.42*0-0.26*0+0.2*1+0.22*1+0.18*1) \\ &= \phi(1.85-0.027SL) \end{aligned} \tag{5.6}$$

$$P(Y=1) = \phi(\mu_1-\beta' X)-\phi(0-\beta' X) = \phi(2.91-0.027SL)-\phi(1.85-0.027SL) \tag{5.7}$$

$$P(Y=2) = \phi(\mu_2-\beta' X)-\phi(\mu_1-\beta' X) = \phi(3.68-0.027SL)-\phi(2.91-0.027SL) \tag{5.8}$$

$$P(Y=3) = \phi(\mu_3-\beta' X)-\phi(\mu_2-\beta' X) = \phi(4.03-0.027SL)-\phi(3.68-0.027SL) \tag{5.9}$$

$$P(Y=4) = 1-\phi(\mu_3-\beta' X) = 1-\phi(4.03-0.027SL) \tag{5.10}$$

Probabilities of injury severity levels under different speed limits are shown in Table 5.3. It can be seen that higher posted speed limits result in more severe injuries for vehicle occupants in vehicle-vehicle crashes. The table also indicates that vehicle occupants sustain lower injury levels in vehicle-vehicle crashes when compared to the injury severity for a pedestrian in a vehicle-pedestrian crash. For example, the probability of moderate injury for an occupant in a vehicle-vehicle crash is 6.35% on a roadway with 55 mph posted speed limit, in comparison to the probability of 38.46% for a pedestrian in a vehicle-pedestrian crash on the same roadway and the same posted speed limit.

Table 5.3 Injury Severities in Different Speed Limits in Vehicle-Vehicle Crash

SL (mph)	P (Y=0)	P (Y=1)	P (Y=2)	P (Y=3)	P (Y=4)
15	0.9251	0.0687	0.0057	0.0005	0
20	0.9049	0.0862	0.0081	0.0006	0.0002
25	0.879	0.1081	0.0116	0.0009	0.0004
30	0.8508	0.1313	0.0158	0.0015	0.0006
35	0.8159	0.1591	0.0218	0.0022	0.001
40	0.7794	0.187	0.0289	0.0031	0.0016
45	0.7357	0.2188	0.0386	0.0044	0.0025
50	0.6915	0.2491	0.0495	0.0062	0.0037
55	0.6406	0.2816	0.0635	0.0088	0.0055
60	0.591	0.3105	0.0788	0.0117	0.008
65	0.5359	0.339	0.0977	0.0158	0.0116

5.2.3 Vehicle and Pedestrian/Bicyclist Crash Prediction Model

As shown in chapter 4, the number of crashes for vehicle-pedestrian/bicycle on Rt. 1 can be predicted using the following equation,

$$N\_Crash = Exp(2.75 - 0.089SL - 0.815UMA + 0.12EXPOSURE) \qquad (5.11)$$

Where

$$EXPOSURE = \frac{AADT * Seglength * 365}{10^6}$$

Thus, the number of vehicle-pedestrian/bicycle crashes for various speed limits can be calculated as in Table 5.4. As explained in the previous chapter, the result that higher posted speed limits on urban roadways are likely to decrease vehicle-pedestrian/bicycle crash frequency may be attributed to the fact that roadways with higher speed limits generally have less pedestrian or bicyclist volume, and the geometric characteristics of those roadways are much better such as wider pavement and more lanes.

Table 5.4 Vehicle-Pedestrian/Bicycle Crash Frequency Predictions under Different Speed Limits

SL (mph)	15	20	25	30	35	40	45	50	55	60	65
Number of Crashes	17	11	7	4.5	2.9	1.8	1.2	0.8	0.5	0.3	0.2

5.2.4 Vehicle-Vehicle Crash Prediction Model

The number of crashes for vehicle-vehicle crashes in each segment of 0.2- mile in length is obtained from the crash prediction model provided in the previous chapter. The crash frequency model is stated as follows:

$$\begin{aligned} N\_Crash = Exp(&1.95 + 0.13N\_Inter + 0.71N\_Siginter + 0.000014AADT - 0.026SL \\ &-0.0069PV + 0.19NOL - 0.38MedGM - 0.42UMA - 1.19UC - 2.5UL) \end{aligned} \tag{5.12}$$

The number of crashes for vehicle-vehicle crashes for various speed limits are presented in Table 5.5. Again, the small number of vehicle-vehicle crashes on roadways with higher posted speed limit may be attributed to the better geometric standards in comparison with roadways with lower posted speed limit.

Table 5.5 Vehicle-Vehicle Crash Predictions under Different Speed Limits

SL (mph)	15	20	25	30	35	40	45	50	55	60	65
Number of Crashes	183	160	141	124	109	95	84	74	65	57	50

5.2.5 Crash Cost

Based on the probabilities of injury severity level, the number of crashes, and the unit costs provided by FHWA, the crash costs in this 1-mile segment of Rt. 1 are described by:

$$CC_{veh-veh} = \sum_{i=0}^{4} P(Y=i) * N\_Crash * UC_i * OP_v \tag{5.13}$$

$$CC_{veh-ped/bic} = \sum_{i=0}^{4} P(Y=i) * N\_Crash * UC_i \tag{5.14}$$

For example, the crash cost for a vehicle-vehicle crash in this segment with speed limit of 40 mph is,

$$\begin{aligned} CC_{veh-veh} &= 95*(0.7794*2590+0.187*24510+0.0289*46620+0.0031*233100+0.0016*3366388)*1.25 \\ &= \$1,669,407 \end{aligned} \tag{5.15}$$

and the crash cost for a vehicle-pedestrian/bicycle crash in this segment with the same speed limit is,

$$\begin{aligned} CC_{veh-ped/bic} &= 1.8*(0.0901*2590+0.497*24510+0.3178*46620+0.0841*233100+0.011*3366388) \\ &= \$150,956 \end{aligned} \tag{5.16}$$

Therefore, the total crash cost in this segment is,

$$C_{crash} = CC_{veh-veh} + CC_{veh-ped/bic} = \$1,669,407 + \$150,956 = \$1,820,363 \tag{5.17}$$

Crash costs under various speed limits are shown in Table 5.6.

Table 5.6 Crash Costs under Different Speed Limits

SL (mph)	Veh.-Ped./Bic. Crash Cost ($)	Veh.-Veh. Crash Cost ($)	Total Crash Cost ($)
15	598,865	1,020,712	1,619,577
20	453,260	1,129,443	1,582,703
25	339,710	1,237,853	1,577,563
30	260,248	1,321,811	1,582,059
35	201,544	1,486,249	1,687,793
40	150,956	1,669,407	1,820,363
45	122,306	1,943,486	2,065,792
50	99,455	2,229,710	2,329,165
55	75,849	2,607,146	2,682,995
60	55,491	3,026,207	3,081,698
65	45,076	3,561,545	3,606,621

5.2.6 CORSIM Simulation Result

Using the previous assumptions, the 1-mile segment of Rt. 1 is simplified to a section with eight intersections, including four signalized intersections. CORSIM input includes field-measured data such as signal timing, geometric characteristics, traffic volume on major roadway, and turn percentage. The output results such as travel time, fuel consumption, and vehicle emissions are provided by the simulation to calculate travel time cost, fuel cost, and vehicle emissions cost using the equations developed in chapter 3. The simulation results for these costs are shown in Table 5.7.

Table 5.7 Costs from Simulation for Route 1

SL	Travel Time (veh-hr)	Travel Time Cost ($)	Fuel Consumption (gal/yr)	Fuel Cost ($)	Emissions ($)			Emissions Cost ($)
					HC	CO2	NO	
15	993,210	23,328,020	451,753	659,559	8,284	3,110	41,757	53,151
20	796,362	18,704,552	411,370	600,600	11,335	4,060	55,804	71,199
25	643,860	15,122,662	406,376	593,309	17,924	6,295	83,950	108,169
30	571,248	13,417,187	417,239	609,169	24,753	8,951	106,621	140,325
35	521,655	12,252,372	443,081	646,898	33,473	12,612	135,977	182,062
40	471,216	11,067,686	468,134	683,476	41,854	16,142	162,038	220,034
45	437,703	10,280,549	494,852	722,484	49,023	19,040	184,370	252,433
50	410,452	9,640,491	521,658	761,621	55,854	21,696	204,569	282,119
55	382,863	8,992,495	555,472	810,989	62,829	24,401	226,998	314,228
60	373,892	8,781,788	585,606	854,985	69,707	27,068	252,042	348,817
65	359,844	8,451,836	620,558	906,015	76,296	29,868	276,700	382,864

5.2.7 Determination of Optimal Posted Speed Limit

The total cost under various speed limits, as shown in Table 5.8, is the summation of all the costs including crash cost, travel time cost, fuel cost, and emissions cost. The equation is stated as follows:

$$TC = C_{crash} + C_{tt} + C_{fuel} + C_{emission} \tag{5.18}$$

It can be seen from Table 5.8 that the optimal speed limit with minimum total cost is 50 mph. Therefore, this speed limit can be selected as the posted speed limit on the 1-mile segment instead of the current 40 mph posted speed limit.

Table 5.8 Total Cost in Different Speed Limits for Rt. 1

SL (mph)	Crash Cost ($)	Travel Time Cost ($)	Fuel Cost ($)	Emissions Cost ($)	Total Cost ($)
15	1,619,577	23,328,020	659,559	53,151	25,660,307
20	1,582,703	18,704,552	600,600	71,199	20,959,054
25	1,577,563	15,122,662	593,309	108,169	17,401,703
30	1,582,059	13,417,187	609,169	140,325	15,748,740
35	1,687,793	12,252,372	646,898	182,062	14,769,125
40	1,820,363	11,067,686	683,476	220,034	13,791,559
45	2,065,792	10,280,549	722,484	252,433	13,321,258
50	2,329,165	9,640,491	761,621	282,119	13,013,396
55	2,682,995	8,992,495	810,989	314,228	12,800,707
60	3,081,698	8,781,788	854,985	348,817	13,067,288
65	3,606,621	8,451,836	906,015	382,864	13,347,336

To present the relationship between speed limit and costs, cost curves based on Table 5.8 are shown in Figure 5.1. The Figure shows that travel time cost gradually decreases while crash cost and vehicle emissions cost increases with the increase of posted speed limit. In addition, it can be seen that increasing posted speed limit reduces the total cost until the speed limit reaches 55 mph, and then the total cost rises with an increasing of posted speed limit.

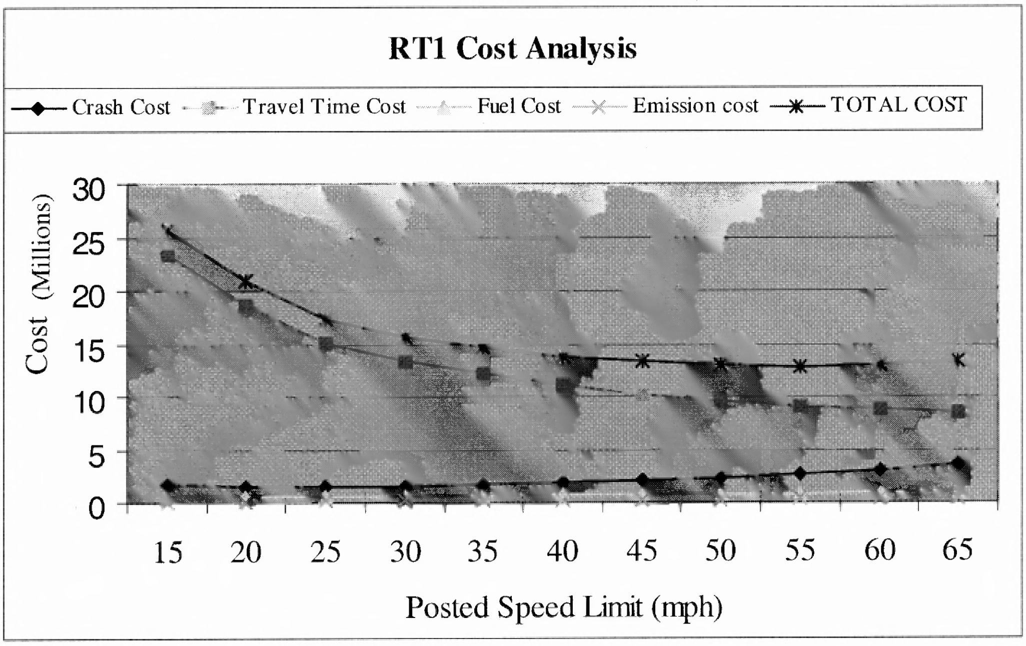

Figure 5.1 Cost curves for route 1.

5.3 Other Case Studies

In addition to the case study for Rt.1, three more roadways, including Rt.30, Rt. 322, and Rt.47, were selected for the optimal speed limit analysis. The total cost calculations and cost curves for each roadway are shown in the following sections.

5.3.1 Case Study 2: Route 30 (Milepost: 41.19-41.79)

RT30 is a roadway crossing multiple counties and it is classified rural principal arterial or urban principal arterial. The selected segment is located in Atlantic County where it is a rural principal arterial. It has an existing posted speed limit of 35 mph. Table 5.9 presents detailed information on this segment, Table 5.10 shows the total costs under various posted speed limits, and Figure 5.2 shows the relationship between total cost and posted speed limit. It can be seen from Table 5.10 and Figure 5.2 that the optimal speed limit with minimum total cost is 30 mph.

Table 5.9 Route 30 Segment Information

Segment	Route 30 (41.19-41.79)
Segment Length	0.6 mile
Location	Egg Harbor City, Atlantic County, NJ
Road Type	Rural Principal Arterial
Posted Speed Limit	35 mph
Pavement Width	40 ft
Shoulder Width	0
Number of Lanes	4
Median Width	0
Median Type	None
AADT	17881
AADTPL (/1000)	4.47
Number of Intersection	16
Number of signalized Intersection	2

Table 5.10 Total Cost in Different Speed Limits for Rt. 30

SL (mph)	Crash Cost ($)	Travel Time Cost ($)	Fuel Cost ($)	Emissions Cost ($)	Total Cost ($)
15	358,236	6,941,143	238,271	4,100	7,541,750
20	434,508	5,450,721	214,097	6,276	6,105,602
25	493,321	4,394,629	206,041	10,073	5,104,064
30	606,522	3,498,252	214,737	14,653	4,334,164
35	808,744	3,455,669	224,074	19,791	4,508,278
40	1,038,655	3,129,897	239,805	25,054	4,433,411
45	1,406,080	2,919,120	245,944	30,413	4,601,557
50	1,843,730	2,784,983	280,732	36,016	4,945,461
55	2,454,354	2,648,709	290,195	41,037	5,434,295
60	3,127,592	2,589,098	322,937	46,351	6,085,978
65	4,029,883	2,499,657	337,261	50,775	6,917,576

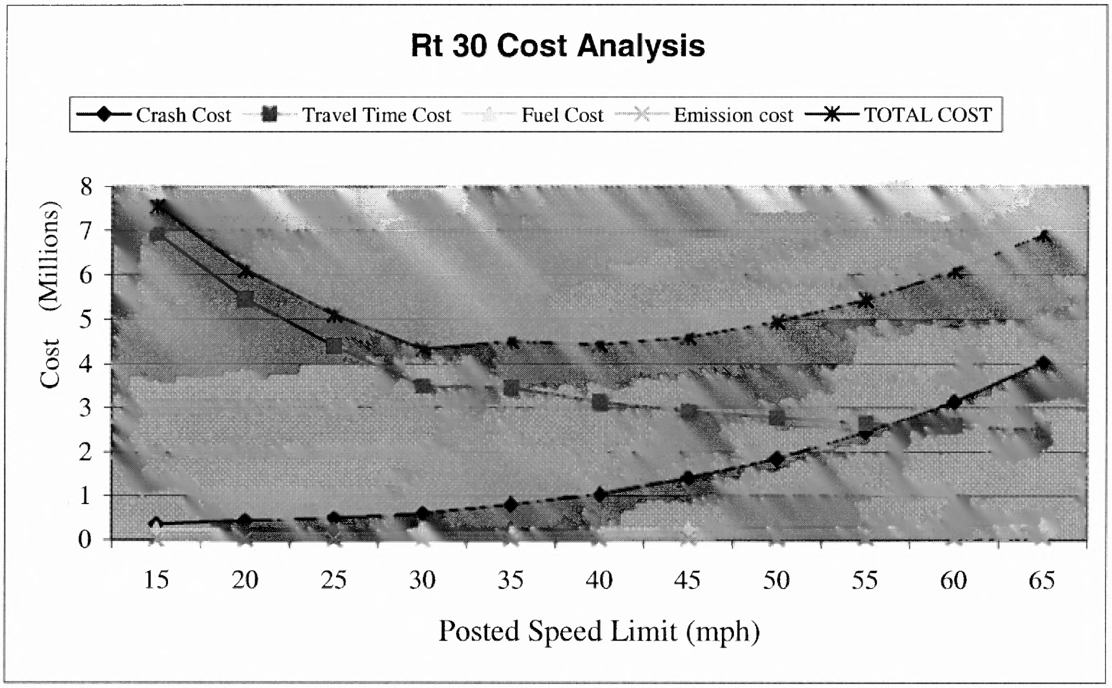

Figure 5.2 Cost curves for Route 30.

5.3.2 Case Study 3: Route 322 (Milepost: 29.74-30.74)

RT322 is a roadway crossing several counties. It has a length of 50 miles, between 2 and 6 lanes, posted speed limit ranging from 30 to 55 mph, shoulder width ranging from 0 to 20 feet, and pavement width from 24 to 72 feet. The selected segment is between mileposts 29.74 through 30.74 in Gloucester County, where it is classified as a rural minor arterial. Table 5.11 displays geometric and traffic information about the segment. Total costs at various posted speed limits are shown in Table 5.12 and Figure 5.3, which indicates that a 40 mph posted speed limit is optimal.

Table 5.11 Route 322 Segment Information

Segment	Route 322 (MP 29.74-30.74)
Segment Length	1 mile
Location	Monroe TWP, Gloucester County, NJ
Road Type	Rural Minor Arterial
Posted Speed Limit	55 mph
Pavement Width	58 ft
Shoulder Width	20
Number of Lanes	2
Median Width	0
Median Type	None
AADT	7060
AADTPL (/1000)	3.53
Number of Intersection	1
Number of signalized Intersection	0

Table 5.12 Total Cost in Different Speed Limits for Rt. 322

SL (mph)	Crash Cost ($)	Travel Time Cost ($)	Fuel Cost ($)	Emissions Cost ($)	Total Cost ($)
15	132,477	4,271,202	187,879	599	4,592,157
20	179,863	3,243,131	158,975	720	3,582,689
25	234,145	2,494,138	143,372	1,058	2,872,713
30	322,819	2,094,005	136,081	1,445	2,554,350
35	452,309	1,806,494	133,012	1,991	2,393,806
40	623,896	1,562,717	133,651	2,449	2,322,713
45	862,865	1,395,439	139,278	3,276	2,400,858
50	1,130,797	1,265,976	148,359	4,506	2,549,638
55	1,567,479	1,144,100	164,475	6,229	2,882,283
60	1,938,895	1,063,397	180,205	8,057	3,190,554
65	2,871,112	9,978,19	192,355	9,732	4,071,018

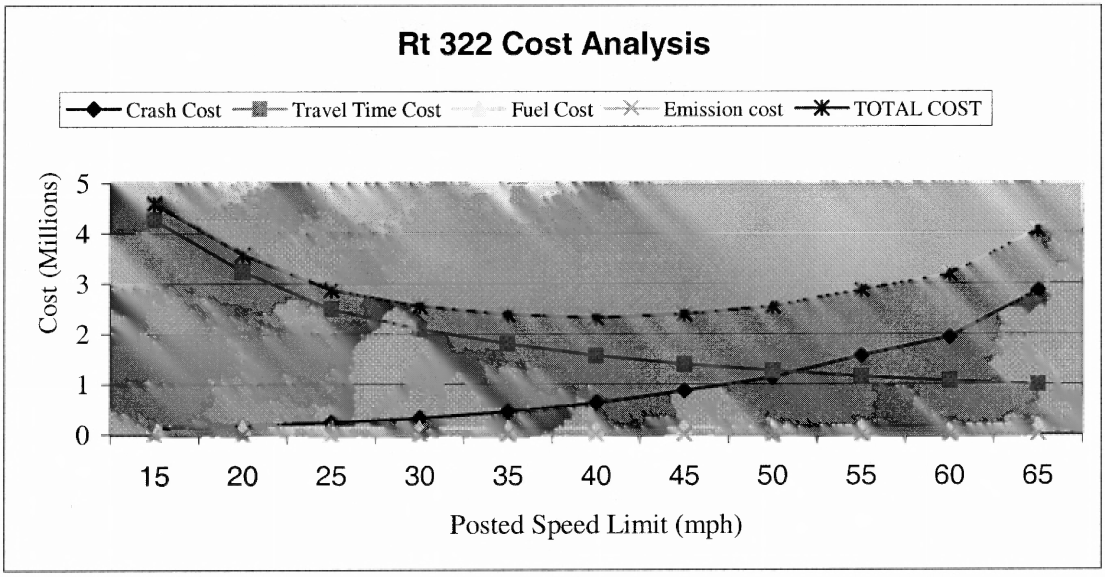

Figure 5.3 Cost curves for Route 322.

CHAPTER 6

CONCLUSION

A major concern about traffic crashes is that through property damages, injuries and even fatalities, they generate large economic costs. The development of a total cost curve in this research provided an opportunity to minimize total cost related to traffic crashes on roadways. Crash injury severity models and crash frequency models for both urban and rural roadways were developed to predict crash frequency and injury severity levels sustained by vehicle occupants, pedestrians and bicyclists. In the case studies, crash costs for segments on different roadways in New Jersey were calculated based on predicted crash frequency and crash injury severity level; CORSIM simulation was used to obtain information on travel time, fuel consumption and emissions to calculate travel time cost, fuel consumption cost, and air emissions cost. Total cost curves were then built to show the relationship between total cost and posted speed limits.

The conclusions of this research are presented in the following sections:

1. Model Development and Model Testing

Seven models were developed in this research. The models include crash injury severity models for motor vehicle crashes in urban and rural roadways, which predict the injury severity level sustained by vehicle occupants; Crash injury severity models for motor-pedestrians/bicyclists crashes in urban and rural roadways, which predict the injury severity level sustained by pedestrians or bicyclists; Crash frequency models for motor vehicle crashes in urban and rural roadways, which predict the number of motor vehicle crashes; and a crash frequency model for motor-pedestrian/bicyclist crashes in urban roadways, which predicts the number of crashes between motor vehicles and pedestrians or bicyclists. The crash injury severity models showed that a higher posted speed limit is more likely to cause more serious injury either for vehicle occupants in motor vehicle crashes or pedestrians/bicyclists when hit by a motor vehicle. The crash frequency models, however, indicated that a higher posted speed limit is associated with a lower crash frequency. This may be attributed to the better road characteristics on roadways with higher posted speed limit.

The likelihood ratio tests for crash injury severity models showed that all models are statistically significant, and the R square test for crash frequency models indicated that the models have good fitness of data.

2. Case Studies

Segments on several roadways in New Jersey were selected for total cost analysis in this research. The roadways include Route 1, Route 47, Route 30, and Route 322. Injury severity models and crash frequency models are developed for these roadways, and crash costs were obtained based on predicted crash frequency, crash injury severity, and unit cost of each injury severity level. CORSIM was used to simulate vehicle operations under different posted speed limits. Travel time, fuel consumption and emissions were provided by CORSIM's output. Operational costs including travel time cost, fuel cost, and emissions cost were then calculated. The total cost curve for each segment showed a U-shape relationship between posted speed limit and total cost. The optimal posted speed limit for each segment was determined as minimum total cost point on the total cost curve.

3. Future Research

Several aspects should be addressed in future research: (a) Data, (b) Model development, and (c) Total cost components.

a. Data

Information on road curve, grade, pedestrian volume, and traffic volume on minor streets was unavailable for this study, although it is much better if the information could be used for the model development. For example, the crash frequency between motor vehicle and pedestrian or bicyclist has been proven to be associated with both traffic volume and pedestrian or bicyclist volume, but the latter variable was ignored in this study, thereby resulting in a biased crash frequency prediction.

b. Model Development

In the process of developing crash injury severity models and crash frequency models, more independent variables should be considered in future studies to better reflect the impact of independent variables on crash frequency and crash injury severity.

c. Total Cost Components

Some previous studies included in the total cost calculation such costs as noise pollution cost, tire-wear cost, and maintenance cost. Therefore, the total cost curve in future studies may account for more cost components to obtain better results.

APPENDIX

NOTATIONS

Variable	Description	Unit
S_s	Social optimum speed	mph
V_T	Value of time	$
P_G	The price of gasoline	$
V_L	The amount necessary to compensate a driver for an increase in the probability of a fatal crash	$
c	The increase in gasoline use per mile as speed increase 1 mph.	gallon
b	The increased probability per mile on driver of a fatal crash as speed increase 1mph	-
b'	The increased probability per mile on other people of a fatal crash as speed increase 1 mph	-
$N\_Crashes$	Number of Crashes per Year	-
Y^*	An unobserved variable measuring the risk of injury	-
X	A vector of non-random independent variables	-
β	A vector of unknown coefficients	-
ε	A random error term	-
C_{crash}	Total crash cost	$
$CC_{veh-veh}$	Crash cost caused by vehicle-vehicle crash	$
$CC_{veh-ped/bic}$	Crash cost caused by vehicle-pedestrian/bicyclist crash	$
UC_i	Estimated crash cost of each injury severity	$

$P(Y=i)$	Probability of each injury severity (i=0,1,2,3,4)	-
OP_v	Vehicle occupancy (person per vehicle)	-
C_{tt}	Travel time cost	\$
C_{fuel}	Fuel consumption cost	\$
$C_{emissions}$	Emissions cost	\$
V_t	Value of time per person	\$
t	Vehicle travel time	h
W_{fuel}	Weight of consumed fuel	kg
V_{fuel}	Price of fuel	\$
W_{NO}	Weight of emission NO	kg
V_{NO}	Unit cost of NO	\$
W_{HC}	Weight of emission HC	kg
V_{HC}	Unit cost of HC	\$
W_{CO}	Weight of emission CO	kg
V_{CO}	Unit cost of CO	\$
TC	Total cost	\$
N_Inter	Number of intersections on a segment	-
$N\_Siginter$	Number of signalized intersections on a segment	-
PV	Pavement width	ft
NOL	Number of lanes	-

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